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Version: Version of Record

Link(s) to article on publisher's website:

<http://dx.doi.org/doi:10.21954/ou.ro.0000d4b3>

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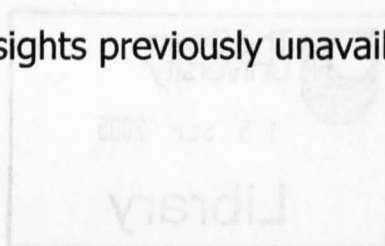
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PhD Thesis:

"Measures from complexity science provide manufacturing companies
with insights previously unavailable to them"



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DATE OF SUBMISSION 24 DECEMBER 2004
DATE OF AWARD 7 JULY 2005

ABSTRACT

"Operational effectiveness" is the means by which market leading value propositions are delivered to customers. The contribution of "operational effectiveness" in manufacturing to competitive strategy has been established. The "operational effectiveness" approach has been based on scientific reductionism, defining itself by list of "best practice" tools, techniques and philosophies. This thesis argues that this had led to loss of the "operational effectiveness" whole, causing variegated success in application of these tools.

Complex systems science, with its origins in communications, control theory and non-linear dynamical systems, has provided previously unavailable insight into real-world systems. The applications to date in manufacturing have been in soft systems appearing either as metaphors or computationally difficult optimisation-type problems.

This thesis argues that manufacturing companies are complex systems. As a result measures for complex behaviour and structure in these systems will yield fresh insight currently unavailable through the reductionist worldview of "operational effectiveness".

This research proposes a new framework of agents that connects the "operational effective" and complex systems views, without the loss of system richness of the complexity worldview. This framework comprises interrelated sets of input/output Entities, produced through Activities carried out by Resources. Novel measures of flow efficacy and the structure of these set-based relationships are then obtained based on this common framework by the use of Entropy and Q-analysis respectively. A methodology for the creation of the framework, its measurement and validation is then proposed and tested.

Three case studies have been carried out in the actual processes of a manufacturing company. The studies have been able to show a consistent benefit from the use of complexity-based measures over and above what would have been available from "operational effectiveness".

Correlation and independence have been observed in the concurrent use of both complexity measures on the frameworks, demonstrating their independence and interdependence.

Pour ma femme Brigitte.

ACKNOWLEDGEMENTS

Thanks to:

- Gerry Frizelle for all your friendship, counsel and wisdom.
- Jeff Johnson for your patience and guidance.
- Brigitte (again) for her love and belief in me, and for putting up with all those lost weekends.
- Our parents Alan and Beryl for their encouragement, and to Jeannot and Dolene for Brigitte.
- IFMA students Alae, Jeremie and Aurelien who each provided shoe leather and grey matter to the case studies with the unflagging enthusiasm and professionalism of their grande ecole.
- Everybody who got their entropy and connectedness measured as part of this thesis.

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ACRONYMS

ABC	Activity Based Costing
ABM	Activity Based Management
ADL	Arthur D Little
BPR	Business Process Re-engineering
CAD	Computer Aided Design
CAS	Complex Adaptive System
CCE	Change Control Engineer
CCR	Capacity Constraint Resource
DFD	Data Flow Diagram
DFT	Demand Flow Technology
EAR	Entity Activity Resource
ECN	Engineering Change Note
ERM	Entity Relational Modelling
ESG	Engineering Services Group
GAAP	Generally Accepted Accounting Principles
GMRG	Global Manufacturing Research Group
GRAI	Graphe a Resultats et Activites Interlies
GST	General Systems Theory
HITOP	High Integration of Technology, Organisation and People
HOOMA	Hierarchical and Object-Oriented Manufacturing Systems Analysis and Definition
IDEF ₀	Information Definition
IFMA	l'Institut Francais de Mechanique Avancee
IMVP	International Motor Vehicle Programme
ISDB	Ink and Solvent Delivery Business
IT	Information Technology
JIT	Just In Time
KS	Kolmogorov-Sinai
LAI	Lean Aerospace Initiative

MRP, MRPII	Materials Requirements Planning, Manufacturing Resources Planning
NNVA	Necessary but Non Value Added (see also VA, NVA)
NVA	Non Value Added (see also VA, NNVA)
OHMS	Order Handling Manufacturing System
OMT	Object Modelling Technique
OOA	Object Oriented Analysis
OPT	Optimised Production Technology
OTIF	On Time In Full
PCB	Printed Circuit Board
PCS	Production Classification System
PDCA	Plan Do Check Act
PPMX	Product Process Matrix
PSC	Planning, Scheduling and Control
QCD	Quality Cost Delivery
QSFV	Quality Speed Flexibility Value
SADT	Structured Analysis Design Technique
SDCA	Standardise Do Check Act (see also PDCA)
SOP	Standard Operating Procedure
SSADM	Structured Systems Analysis and Design Method
TFP	Total Factor Productivity
T-I-OE	Throughput-Inventory-Operating Expense
TPS	Toyota Production System
UML	Universal Modelling Language
VA	Value Added (see also NVA, NNVA)
VM	Visual Management
VSM	(context of cybernetics) Viable Systems Model
VSM	(context of lean production) Value Stream Mapping
WCM	World Class Manufacturing

CHAPTER 1 - INTRODUCTION

1.1 Introduction to the thesis

This thesis examines the following hypothesis:

"Measures from complexity science provide manufacturing companies with insights previously unavailable to them"

The basis for the research is that the null hypothesis:

"Existing knowledge can provide (at least) the same insights as those which may be obtained using measures from complexity science"

can be shown to be false. To do this a theoretical framework has been developed and applied in three case studies. The aim is to show that the framework highlights issues that would either be missed or misinterpreted by the use of existing measures.

The research has been motivated by the observation that manufacturing companies are complex systems.

For the purposes of this thesis, complexity science is defined as the study of the theory and application of complex systems. There is no universally accepted definition for a complex system. However, a complex system is one that exhibits some or all of the following characteristics:

- It is made up of a number of agents, interacting with one another and their environment using rules;
- The agents produce emergent behaviour; similarly, the system cannot be reduced or is computationally irreducible;
- The system is sensitive to small changes, path dependence and deterministic chaos;

- Connectedness between agents is very important. The agents and their connections are often multi-level in architecture.

The relationship between these properties and the modern manufacturing system is established more fully in section 1.3.

To set about challenging a null hypothesis so constructed, it is necessary to understand if the literature of manufacturing “operational effectiveness” challenges, complements or ignores the complex system view of the manufacturing company. This is the first research question that this thesis will address:

Question 1

Does the literature on “excellence”, especially as “operational effectiveness”, challenge, complement or ignore the complex systems view of the manufacturing company?

In this context the null hypothesis requires that there is nothing in the complexity literature that informs the concept of excellence that does not already exist in the literature on excellence.

This is the subject matter of chapters 2 and 3, from which it will be shown that conventional literature is largely free from the influence of complexity science. On the other hand, it will be shown that there are concepts in complexity science that give significant new insights into excellence in manufacturing companies. In other words, it is the complexity science community who are making inroads into this field, even if it is very limited at the time of writing this thesis. Measures of “excellence” are key to understanding the operation of manufacturing systems. Understanding to what extent conventional measurement supports the complex systems view will further challenge the null hypothesis. The second research question is therefore:

Question 2

Do the current measures of “excellence” support a complex systems view of the manufacturing company?

In this context the null hypothesis requires that current measures of excellence give all the insights that complex systems measures of excellence can give.

This is addressed in chapters 2 and 3, where it is possible to conclude that there is no significant linkage between conventional measurement and the measures of complex systems, the only exception being work using uncertainty principles (Palmer and Parker, 2001). This thesis shows that there are other measures from complex systems science that do indeed give significant new insights into the complicated business of measuring and operating a manufacturing system.

Returning to our definition of a complex system (see above), the role of agents is key, and this thesis proposes that agents are critical to the study of manufacturing company. To support a complex systems view of the manufacturing company, it must be possible to identify the agents of interest and their interactions. Research question 3 is therefore:

Question 3

What are the agents of interest in a complex manufacturing system, and what are their interactions?

In this context the null hypothesis would be that the conventional approach either contains the concept of agents, or that there are no insights to be gained from it.

The literature shows that agent-based simulation is used to solve difficult optimisation problems, but the concept of agents is not in widespread use. It will be shown in chapter 4 that this research has contributed a novel framework for the representation of a manufacturing (complex) system comprising input/output Entities, realised through processes made up of sequences of Activities, carried out by Resources that are mapped to them. In this model it will be argued that the resources can be regarded as agents, providing a counter-example to the null hypothesis in which complexity science does indeed provide new insights.

With a manufacturing system represented as a framework of complex system agents, it is further possible to test the null hypothesis by defining how the patterns of complex structure and behaviour relate to the conventional measures for “operational effectiveness”. Research question 4 is therefore:

Question 4

Using complexity science, what are the patterns of operational effectiveness in terms of both structure and behaviour? How can they be measured for study?

The null hypothesis here is that complexity science provides no new patterns of operational effectiveness, or the patterns it produces provide no new insights.

Chapter 3 will show that there are various patterns (measures) of complex behaviour and structure arising from complex systems that are of interest.

Chapter 4 develops a new model based on complex systems that shows how these measures may be related to operational effectiveness.

The structural pattern (Q-analysis, Atkin, 1974) used is geometric based on relations between (i) agent-resources and the activities they are able to carry out, and (ii) how activities are defined in terms of the entities they produce. It will become clear that this structure can be related to the internal states of the agents.

The resulting behavioural pattern is the flow obstruction in a network of queues whose nodes are servers (entropy, Frizelle and Suhov, 2001). These queue servers are simply the resources. The importance of queuing behaviour has been widely recognised but never explicitly measured in conventional “operational effectiveness”.

A definitive way to reject the null hypothesis would be to develop a complexity-influenced model of measures on a structural framework, leading to research question 5:

Question 5

What would a complete complexity-influenced model using measures look like, and how would it be applied?

This question takes us the heart of the thesis: here the null hypothesis is that a complexity-influenced model would fail to provide any new insights into manufacturing companies.

The complexity-influenced model described in chapter 4 is operationalised as a methodology in chapter 5 and empirically tested in chapters 6,7 and 8. This shows both what a complexity influenced model looks like, and how it is applied. Each of the case studies in chapters 6, 7 and 8 contributes to the thesis by showing the different ways in which the complexity-based measures selected can give novel insights into manufacturing processes under different circumstances. These insights could not have been obtained by using "best practices" from the "operational effectiveness" literature alone. The use of the model is able to show that the null hypothesis may be definitively rejected.

To go beyond this, having established that complexity science can give new insights into manufacturing systems, two further research questions are posed:

Question 6

Can this complexity-influenced model be placed on a spectrum including strategic planning and operational execution?

The response to research question 6 is framed in chapter 5, by setting a taxonomy for the case studies that allows a range on contexts for the case studies. The subsequent case studies in chapters 6, 7 and 8 show more evidence for the use of the model in the operational than strategic end of the spectrum. However, there are some useful insights that may support strategic decisions making, and this is further reflected upon in chapter 9.

Question 7

Can this complexity-influenced model show researchers and practitioners what "absolute excellence" would look like, without empirical bias of specific approaches or "best practice" prescription of tools and techniques?

This question is also addressed by the case studies, in chapter 9 it is possible to conclude that the complexity-influenced model developed in this thesis adds to the vocabulary of "operational effectiveness" by the additional insights it gives. This model then can be shown to augment, not refute the current paradigm of "operational effectiveness", even if some counterintuitive insights are provided in the different case studies.

Having now established how the null hypothesis will be disproved in support of the thesis, and the additional insights this can give, a more detailed introduction into complex systems and the current view of "operational effectiveness" are given in the remainder of this chapter.

1.2 The state of the art in manufacturing knowledge

There is a large pool of human knowledge devoted to the means by which products are manufactured. The definition of manufacturing used throughout this thesis is that:

"Manufacturing is the organised activity devoted to the transformation of raw materials into marketable goods" (Wu, 1992).

This pertains to the processing of physical materials and information. It includes the application of the physical sciences to the transformation of the physical materials, and to the synthesis of these instances of transformation and their organisation into viable systems of wealth creation. This thesis is concerned with the latter.

Human knowledge in this area is extensive and diverse. Whilst it is not the objective of the thesis to classify this knowledge, a diverse vocabulary for the types of knowledge exists, ranging from

philosophical underpinnings through to operational execution. At all levels in this ill-defined continuum, this vocabulary can take the form of measurements, models, systems, methodologies, tools, and techniques. These terms are neither mutually exclusive nor completely exhaustive. Within this variety there is a range of emphases taken by each researcher and practitioner. The result is that even before the type of manufacturing process is considered in any depth, there is a large product space of possible tools *etc.* available. The parameters making up the dimensions of this space can be, and are, disputed. For the manufacturer to position themselves optimally or even effectively within this space is a major challenge.

The competitive landscape in which this product space must be navigated is constantly changing, including:

- The acceleration of innovation cycles of process technologies and products;
- Pressure from global competition;
- Improved ease of acquisition of know-how by suppliers and customers;
- Increased segmentation of markets, customer sophistication and elevated expectations;
- Increased regulation and legislation in more established economies, reflecting the stakeholder view of the activities of the manufacturer.

The solution to this is the adoption of “best practices”, which positions the manufacturer in certain parts of the product space by imitating so-called “excellent” companies to match their perceived excellence. This sharing is essentially a collaborative activity in the midst of fierce competition. The hazard of this approach is that pursuing best practice can lose the distinctive proposition to customers offered by a manufacturer. Best practice emulation involves copying so it will be therefore only a short-term improvement, and an escalation in a zero-sum game. It must also be remembered that “best practice” is a moving target for people following it. The trajectory of best practice has gone from Ford (mass production) to General Motors (mass production with product variety) to Toyota (lean production), and so to agile models of the type widely discussed (such as in Kidd, 1994), an archetypal exemplar of which has yet to emerge. This progression is shown in figure 1.1.



Figure 1.1 – The state of the art in manufacturing

The approach of attaining “excellence” based on best practices also has a legacy of failed implementations, and partial successes that do not achieve the full potential of the practices that they have inspired. For example, Liker (2004) gives the example of a US company that had won a prestigious Shingo award, but when the Toyota Supplier Support Centre carried out a further lean manufacturing project at this site, they found that further improvements in key indicators of 46-91% were possible. This shows that despite the extensive literature in lean manufacturing, that “expert” practitioners were not capable of achieving comparable results given the same public domain knowledge.

Summarising the “excellence” literature reveals that there is a language of excellence, supported by a vocabulary of specific practices and good comparable performance in key performance indicators, which are outcome measures. However, “how to achieve this” is then a fragmented field, disconnected formally from these desirable outcomes. It is reduced to a mixture of philosophy/guiding principles, empirically derived rules of thumb, tools and techniques. Successful implementation and control is then measured by further, localised outcome measures, principally connected to time, cost and quality. “Excellence” is then an emergent phenomenon.

1.3 The lack of influence of complexity science on performance leadership in manufacturing

The highly complicated parameter product spaces mentioned above have given rise to the concepts of complexity in organisations, more recently supported by a set of physical science-based concrete mathematical terms for this phenomenon. This knowledge has merged with an

established study of complexity already ongoing in manufacturing organisations (Flood and Carson, 1993). This study had the objective of “dealing with complexity”, and included the influence and actions of people in systems otherwise viewed as linear, deterministic and analogous to the control of machines. The increased availability of powerful computing and programming tools to support the description of organisations as being other than machine-like, has led to a new area of scientific study referred to in this thesis as complexity science. This has provided the disciplines of computing and control, behavioural and biological sciences, economists and management theorists, operations management and operations research with a common language to describe traditionally difficult systems.

These systems have a number of agents; component parts each capable of acting according to their own rules and developed mechanisms. Their rules will also determine whether their behaviour is collaborative or competitive. The outcome of the actions of these agents is an emergent phenomenon. It may not be attributed to any single agent, and the system state will be highly sensitive to small rule changes and different initial conditions. Over time they will undergo adaptation and be self-reproducing. The modern manufacturing environment is certainly an example of a system that fits this description.

Since the emergence of complexity science and the complex system into their current forms, there have been numerous successful applications where agent behaviours have given insight into difficult problems in manufacturing. Examples include logistics systems (Wakefield, 2001) and auctions and distributed control of automated production equipment (Moody and Morley, 1999). With a very few noteworthy exceptions, there has been no linkage between the established best practices in manufacturing and the complexity science view of the manufacturing system. One such example is the use of cladograms to classify the adoption of best practices within an industry sector, to facilitate change management (Tsinopoulos and McCarthy, 2000). Jones (2002) makes the assertion that whilst an area of tremendous interest and highly appropriate for researchers, the actual influence of complexity is almost non-existent in mainstream manufacturing.

1.4 Conclusions

This chapter has identified the thesis and null hypothesis against which it will be tested. A roadmap for the development of the thesis has been described by a series of research questions, with guidance on how the following chapters will address them.

Having now chartered the construction of the thesis, the next chapter will begin that process by identifying the state of the art in conventional “operational effectiveness” literature. It will also show how a reductionist approach to its study has led to a loss of the emergent property of the whole, until recently, understanding of its essence.

CHAPTER 2 - CONVENTIONAL THEORIES OF "EXCELLENCE", BEST PRACTICE AND "OPERATIONAL EFFECTIVENESS" IN MANUFACTURING

2.1 Introduction

This chapter and Chapter 3 will look at the influence and cross fertilisation of ideas between "operational effectiveness" literature prevalent in manufacturing and complexity science literature. This chapter will concentrate on conventional literature of "operational effectiveness" and its measurement, to identify the influence of the complexity sciences. It will be shown in the remainder of this chapter that there is little evidence of the complex systems view in "operational effectiveness". This will be structured as follows.

Section 2.2 summarises the origins of the current "operational effectiveness" concept, and the origins and motivations towards it from the previous paradigm. Section 2.2.1 defines operational effectiveness in terms of the achievement of a strategic goal through excellence in execution. The literature through which "operational effectiveness" established itself as crucial to an overall competitive position through manufacturing strategy is also reviewed.

Section 2.2.2 summarises how measures for operational effectiveness have evolved to meet the expanded strategy role for manufacturing operations, and looks for evidence of the introduction of complex systems thinking.

Section 2.2.3 will summarise the previous paradigm of manufacturing thinking to show how "operational effectiveness" is different and how it has been more successful. An early awareness of the concepts of complexity was shown in this paradigm from the point of view of how to deal with complexity in production operations necessitated by the paradigm.

Section 2.3 will then develop a meta model for the operationally effective manufacturing system in its current state of the art. This will include:

- Emergence of this new type of organisation, and how they were first recognised (section 2.3.1);
- Form and underpinning elements of this model (section 2.3.2);
- Insights from discussions of how to adopt this model as a *modus operandi* (section 2.3.3).
- Penetration of this model in various forms across manufacturing activity (section 2.3.4);

In section 2.4 the newest form of the organisation – the agile competitor is introduced and the novelty and adoption of complexity science thinking is again reviewed for this fledgling (and as yet largely unproven) organisation form.

Very limited influence from complexity science will be shown throughout, supporting the thesis that there may be novelty and fresh insight to be gained from the use of measures from complexity in manufacturing systems.

Finally, in section 2.5 a description of the current methods for representing manufacturing systems and modelling them will be given, and in section 2.6 conclusions are drawn.

2.2 Motivation and measurement of “operational effectiveness”

2.2.1 Competitive strategy and operational effectiveness

The literature on competitive advantage, strategy (manufacturing strategy in particular) and strategy translation into practice is vast. This has co-evolved with global market changes and new technologies. Given the high degree of traceability employed by writers in this field to their predecessors, only the most current thinking is covered here. It will be shown that whilst a mature role for operational effectiveness has been developed by various researchers, its

integration into a competitive strategy for a company in a market place has not drawn on any of the ideas of fitness or adaptation that complex systems have to offer.

Excellence in organisations has been expressed as a commitment to the customer for the product or service provided, and as an investment in the individuals expected to provide that commitment within the organisation. Most recently this commitment has been interpreted as providing an environment where employees can innovate (Peters and Waterman, 1982; Peters, 1997).

Porter (1996) reasserts the traditional view of strategy with respect to his "five forces" model (suppliers, customers, competitors, substitutes, entry barriers). He then goes on to assert that after years of pursuing internally focussed initiatives in improving how companies work, distinctiveness and competitive advantage cannot be found in best practice alone. *Operational Effectiveness is not enough*. It is a zero-sum game in the same way that price competition is.

He views that a distinctive proposition to customers is required and to the implied capabilities to be able to offer them. This implies that "operational excellence" is a universal requirement, and should be pursued in addition to distinct capabilities, without defocusing the organisation from this principal goal. Hill (1985), by analogy with how products themselves are offered and provided, defines operational excellence as an order qualifier, rather than an order winner. The absence of an explicit strategy, Hill argues, has created a vacuum often filled by "flavour of the month" solutions modelled on current "best practices" only.

This view is true for stable markets at an equilibrium position, which is valid for many markets for products in the short to medium term. The view is that operational excellence is not a source of innovation that can affect competitiveness. Where markets are more dynamic (prone to radical displacements from equilibrium and creation of niches), then this definition is less easy to support.

(Treacy and Wiersema, 1995) express this search for distinctiveness in a slightly different way. They argue that companies wishing to be distinctive are most successful if they concentrate on leadership in one of three positions

- Product leaders
- Customer intimate
- Operationally excellent

whilst continuing to qualify themselves for customers. Their view is that this is context and market specific, but that sometimes the differentiation and market speciation can come from the very act of offering an alternative value proposition to customers. This can include radically lower prices for products. Innovation, rather than copying of best practice is advocated, albeit being the very best in your chosen discipline is then essential.

One of the clearer illustrations of this is the introduction of continuous casting in steel minimills by Nucor. Minimills were able to compete with the economies of scale of larger integrated processes (Preston, 1991). Operational excellence, expressed in this particular case as early adoption of manufacturing technologies and capabilities is the very basis for how Nucor were able to succeed. The steel market was certainly not in equilibrium during this time.

Brandenburger and Nalebuff, (1996) take the five forces model and add a further factor of “complementors” (organisations who can both create, expand and compete within a market for products) in their exposition of game theory. Using an expanded framework to include the complementor in the firm’s dynamics, they show how their basic principles can be applied to both improving a competitive position in relatively static markets and complete market reinvention or creation, citing examples from the airline and the video games industries respectively. There is a very clear emphasis on capturing value from a market by using the model to have an enhanced understanding of the dynamics of competition and co-operation and how they are best applied.

Having asserted the importance of “operational excellence” in a variety of strategic positions, it is useful to look briefly at how companies develop manufacturing strategies as part of business strategy.

The role of manufacturing in the organisation is expressed as four stages from the reactive (whereby it seeks to minimise its negative impact from actually having to make/process things) to the proactive. In the latter case, manufacturing is a source of significant advantage. Hayes *et al* (1988) describe an expanded set of co-ordinated decision of “bricks and mortar” provision of:

1. The amount of total production capacity to provide;
2. How this capacity should be broken up into specific production facilities (how they should be specialized and where they should be located);
3. What kind of production equipment and systems to provide those facilities with;
4. Which materials, systems, and services should be produced internally and which should be sourced from outside the organisation (and what kind of relationships should be established with outside suppliers);
5. Human resource policies and practices, including management selection and training policies;
6. Quality assurance and control systems;
7. Production planning and inventory control systems;
8. New product development processes;
9. Performance measurement and reward systems, including capital allocation systems;
10. Organizational structure and design.

This evolution is described and supported in detail, with the objective for the organisation being the transition from the reactive to the proactive as the basis of competitive challenge. Hayes *et al* (1988) describe four distinct stages of contribution of the manufacturing capability set to a competitive position. They argue that there is a transition in the contribution that manufacturing can make to the competitive position of a company in its market. They define this as from Stage I, of not disrupting the operation of the company, to Stage IV whereby the company leverages its manufacturing to out-perform competitors.

A summary of the reconciliation of strategy (what the other business functions require of manufacturing based on where the organisation is on the continuum) against specific dimensions of manufacturing capability development (conversion process selection, positioning, product focus in operations *etc.*) is also given in Hill (1985).

Perspectives on manufacturing strategy have also been summarised (Leong and Ward, 1995) as six P's, building on existing work on views of general strategy in the firm. This is noteworthy because it unifies earlier notions of strategy to the concept of a split between the strategy making process (external fit) and the content (internal fit) aspects of strategy – namely:

- Planning activities as part of a hierarchical corporate structure;
- Proactiveness in anticipating the future and acquire technology/capability in advance of needs;
- Pattern of actions / decisions taken by a manufacturer in nine general categories;
- Portfolio of manufacturing capabilities;
- Programmes of improvement;
- Performance measurement aligned to the objectives of the strategy.

Developing the disparate ideas, a retrospective on manufacturing strategy as a process in itself has been proposed (Voss, 1995). Rather than taking these as perspectives or parts of a whole, this view looks at the distinctiveness of three strands of thinking about strategy:

- Strategic choices in manufacturing;
- Pursuing best practices;
- Competing through manufacturing.

Voss argues that these are not mutually exclusive but actually fit into an improvement cycle and are thus complementary. The different emphasis placed on tools and techniques and management patterns of activity are actually part of a Deming cycle of plan-do-check-act. Each of the six perspectives comes into play with different emphasis at different times, as shown in figure 2.1:

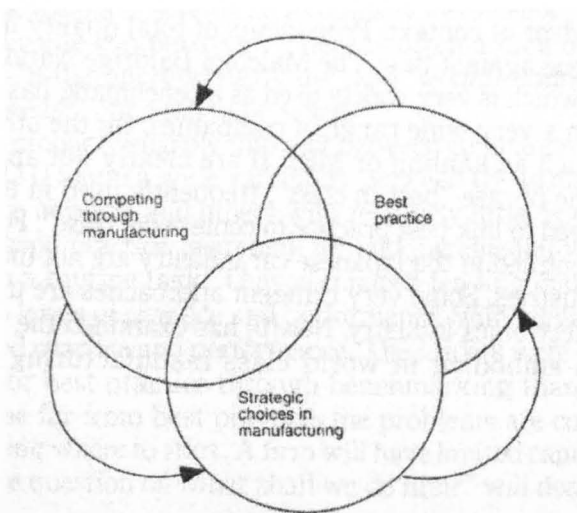


Figure 2.1 – Improvement cycle for manufacturing strategy (Voss, 1995)

This is a more dynamic view than the Hayes and Wheelwright four-stage model and perhaps reflects more awareness of environmental (market) change and systems dynamics rather than the stable equilibrium, as noted in the classical competitive strategy development, discussed above.

The development of a particular competence set and offering high performance to capture value from a market is the continuous theme of this view of strategy. This is true regardless of whether it is an intimate part of the firm's value proposition (helping to provide a unique product or service) or implied to qualify a firm in a marketplace (by being able to offer the product or service at the correct quality, price and responsiveness). This leads naturally into a discussion of the literature of performance measurement and manufacturing "operational effectiveness", whether manufacturing is viewed as being at the heart or periphery of an overall strategic vision.

It can therefore be concluded that a sophisticated and demanding role is required of the manufacturing capability of a modern organisation (exemplified by how strategy is made to offer the right manufacturing response for a broader competitive position). However, there is no evidence of the adoption of complex systems ideas in how strategy is formulated to offer a desired response. There appears to be no influence of complexity into "operational effectiveness" from the strategic demands placed on manufacturing.

2.2.2 Performance Measurement

To measure the effectiveness of a strategy and its execution, various internal measures are required to measure operational effectiveness. The immediate paradox is that until relatively recently, companies made no effort to measure the same things they used to describe their strategy:

"A surprising number of companies describe their strategies in terms of customer service, innovation, or the quality and capabilities of their people, yet do little to measure these variables."(Eccles, 1991)

Companies have traditionally measured and reported exclusively in financial only terms. Hayes *et al* (1988) argue that in the West:

"Financial measures became the principal means of monitoring manufacturing performance, identifying problems, and pursuing opportunities for growth. In the hands of an executive who had little understanding of either operations or science, a control system dominated by such financial measures as return on investment (ROI) could easily lead to a failure to invest in equipment, worker capabilities, or new technology. Likewise, developing new products without taking into account their manufacturability or the diversity of the demands they placed on manufacturing often led to unfocused facilities that tried to be "jacks of all trades" and ended up being masters of none."

Furthermore, they argue successfully that the Generally Accepted Accounting Principles (GAAP) and their analogues across the Western nations has led to companies adopting similar performance measurement and reporting systems, regardless of their competitive strategy or approach to manufacturing. This is a good example of how measurement is driving the wrong behaviour. Their proposal to remedy this was the Total Factor Productivity measure (TFP), based on the output number of units of a product for a given sum of resource inputs to achieve it, re-

calculated as an index over time in the most recent base prices (thereby removing the effect of price changes). This displaced the traditional and exclusive focus on direct labour as the source of cost in modern manufacturing systems.

The first challenge to the primacy of financial measurement came from the quality movement in the 1980's. To provide a foundation for an expanded measurement framework, Drucker described a foundation for measurement as comprising the following information requirements (Drucker 1995):

- *"Foundation – are the financial objectives being achieved;*
- *Productivity of the organisation producing the results;*
- *Relative measures of organisation competence (as a source of competitive differentiation);*
- *Effectiveness of resource allocation."*

Even in addressing these, it has been observed that there is often a complete misalignment of measuring the various organisation functions, such that

"...evidence of the cost orientation can be found in the cost-centre role traditionally assigned to operations. In many manufacturing firms, unit-manufacturing cost is still a primary measure of performance, whereas marketing is driven by revenue targets."
(Karmarkar, 1996)

Karmarkar (1996) correctly notes the problems of missed opportunity from lack of alignment on measures across functions, but at the same time he does not concede that a low cost position can contribute to a stronger competitive position, regardless of organisational alignment. His view is that there are still trade-offs to be made in how organisations operate. This is in contrast with the "one best way" of the "operational effectiveness" view whereby excellence in all areas can be attained by following *e.g.* lean principles. The significance of cross-functional alignment of what is measured (especially in process-oriented organisations, in section 2.3) is particularly relevant when a further element is introduced, namely how it is measured:

"Marketing tracks market share, operations watches inventory, finance monitors costs... Such results measures tell an organization where it is but not how it got there... in contrast, process measures monitor the tasks and activities that produce a given result." (Meyer, 1994)

The advantage of process measurement applied across the entire value stream for a new product (in the context of market entrants) has been qualified by Drucker (1995):

"... the newcomer also enjoys a tremendous cost advantage. Usually about 30%. The reason is always the same; the new company knows and manages the costs of the entire economic chain rather than its costs alone. Toyota is perhaps the best-publicized example of a company that knows and manages the costs of its suppliers and distributors; they are all, of course, members of its keiretsu." (Drucker 1995)

An expanded discussion of process measurement in cross-functional processes of lean producers is made by (De Toni & Tonchia, 1996). They use the following definition of a process as:

"... a sum of activities, each composed of operations consuming resources – can be looked on as the place where the added value develops. Each process is moved and directed towards the customer and contributes, together with others, to his/her satisfaction."

Using Drucker's (1995) criteria for measurement with this definition, process and performance measure are actually intimately linked. In De Toni and Tonchia's (1996) case study of process management, and starting from the established measurement trade-off rationale of Quality, Cost and Time (Delivery in section 2.3.2), they have identified three "synthesis indicators":

- Horizontal synthesis along a process;
- Vertical synthesis amongst different measures in a process (the scope of the traditional trade-off);
- Organisation performance in a multi process system.

This expands the need for process measures rather than strict result-only measures. It is an interesting way to view process efficacy, overall process performance and organisational capability in a particular respect. It also negates the traditional view of the trade-off and the assumption that “you have to choose between” Quality, Cost and Time (Delivery). As such it is an interesting initial development away from traditional process measurement.

The continued role of finance in process measurement is evident in the development of Activity Based Costing (ABC). ABC is the combination of traceable cost drivers from management accounting with the mapped processes of product value streams, as shown in figure 2.2. This can be contrasted with the apportionment of indirect and support costs (expressed as overheads) to products, often distorting real costs of product families, leading to flawed investments *etc.*, and damaging improvement programmes (Ahlstrom, 1996). The direct-indirect distinction is ignored in ABC. This transparency is seen as a major tool in assuring competitive advantage (Kidd, 1994)

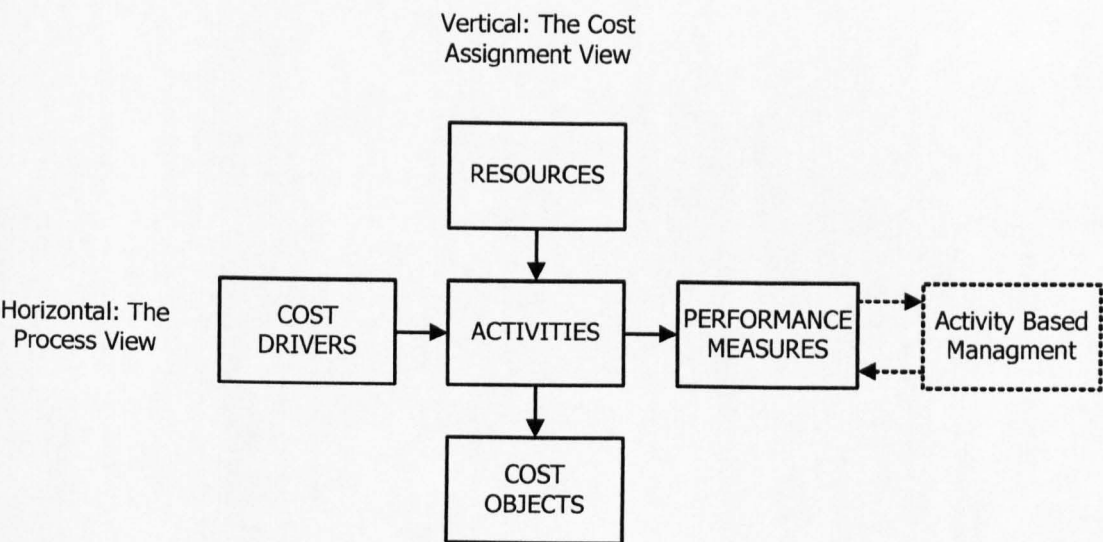


Figure 2.2 - The CAM-I Activity Based Costing Model (Kidd, 1994, p239)

The benefits of ABC, and also how initial problems encountered with programmes can be overcome (by aggregation of data without loss of resolution and accuracy), have been outlined:

"Most companies [embarking on Activity Based Costing] collect excruciatingly detailed information, which overwhelms both their people and their computer systems. When Chrysler installed ABC at its first factory... it gathered three times the information it could use practically... Similarly, Chrysler's Mopar replacement-parts operation found itself overwhelmed by data when it attempted to construct ABC costs for each of the 250,000 parts that it stocks. Mopar ultimately decided to construct the costs of 60 major and minor product groups, which reduced the amount of data to a manageable level but was still extremely useful." (Ness and Cucuzza, 1995)

Critics of ABC include (Schonberger, 1996) who argues that ABC adds nothing to the value of a measurement over and above the good principles of process management. This criticism is also offered, with a suggested improvement (Goldman *et al*, 1995) by Goldratt's framework whereby performance is the (T-I-OE) Throughput (sales value achieved), minus both the Inventory (valued at purchase cost) and Operating Expense (the actual cost of conversion of inventory into something that has been sold). The key difference between ABC and T-I-OE is the proposition that partly converted materials have any value. ABC is more accurate and transparent than traditional (apportionment) cost accounting. ABC stops short of T-I-OE, which focuses on the emergence of value only when the item has been sold to a customer. In conclusion, ABC is useful as a tool to accurately assess product costs. T-I-OE goes further, and is an operational measure. It is therefore a simplified measure in support of process measurement.

The most widely recognised attempt to provide an all-encompassing measurement agenda has been the Balanced Scorecard (Kaplan and Norton, 1992). This is a major pan-organisation measurement system, including:

- Finance;
- Customer Satisfaction;
- Process Performance;
- Individual and team learning/development.

Ten years after its first publication, a major survey of scorecard users' experiences (Olve *et al*, 2003) showed that the major use of scorecards was as a reality check and to drive the logic of a particular strategy top-down through a business. (Financial returns will be achieved from satisfied customers. Customers are satisfied by process performance. Process performance and further improvement are ensured by individual and team development.

The contribution of bottom-up measures (demonstrated clearly by quality measures) is the basis of the "six sigma" concept, such as rolled yields or service level measurements. Six Sigma is based on using process performance to deliver the "value entitlement" of customers and their suppliers. Whereas the scorecard tends to be top-down, the "best-in-class" six-sigma approach is entirely bottom-up (Gane *et al*, 2002).

The top-down contribution of the scorecard system is used to align sub-functions both horizontally (along a process) and vertically (within the competences of a function). This has also led to a bottom-up planning process using scorecards, complementing the traditional top-down view of strategy (Olve *et al*, 2003).

This summary of performance measurement shows that the methods and scope of measurement have broadened from purely financial outcomes, and that measurement systems now possess many facets and perspectives of a manufacturing system. This change (*e.g.* with the development of the balanced scorecard) is acknowledging the richness of the manufacturing system but makes little or no attempt to understand the complex interactions of the employees, customers, process parameters and finance over and above simple causation from linear rules. Thus it is more exhaustive but essentially still reductionist in outlook.

The alignment of measurement to the value adding process from both the T-I-OE and ABC measures appear to reinforce the credibility of process basis for organisation. This view is critical to the contemporary view of operation effectiveness to be discussed in section 2.3.

2.2.3 Precursors to contemporary “operational effectiveness”

Womack *et al* (1990) describe the fundamental differences in performance and appearance between western organisation of manufacturing and the then new Japanese form. Western manufacturing will now be summarised briefly to look for evidence of complex systems thinking.

This form of organisation was predicated on:

- Measuring the return on asset utilisation of fixed assets;
- High volume production on automated equipment, with process knowledge residing with the Original Equipment Manufacturers (OEM). Consultancy Arthur D Little (ADL, 1997) observed this in their work with branded goods manufacturers to help clients compete through gaining process knowledge often never properly transferred from OEM's with the pan-industry equipment they sold. These OEM's often effectively dictated scale economies.
- Lead time follows from the constraints of scale economies and the need to have high asset utilisation;
- The utilisation culture encouraged a “no-stops” ethos of end of line inspection (sorting or scrap) and rework.

Given these constraints, operations research focussed on complicated algorithms to optimise performance, and the fledgling computer industry focussed on software systems to handle the huge amounts of data created to reconcile customer requirements with products. This work is described in Wight (1984).

Academic frameworks were also developed to fit this model and its forms into the situational variety and different production variety of different products markets. The product process matrix (PPMX) was first proposed by Hayes and Wheelwright in 1979 (Ahmad and Schroeder, 2002) to explore the fit between market and manufacturing strategy, and the dynamics of process selection for a market entry or exit. Similar classification for processes was discussed in Schmitt *et al* (1985).

It was a successful attempt to provide a classification framework for the flexibility versus configuration of manufacturing (*i.e.* how these organisations function to provide the response required of them by their customers).

The PPMX has been further developed. The classification scheme that it introduced into types of manufacturing process has been expanded by various studies focussed on specific process and subject areas:

- Flow lines (Aneke and Carrie, 1984) were exhaustively classified into sixteen theoretical groups, it being possible to implement ten from this set;
- Repetitive Manufacturing (Spencer and Cox, 1995) was studied in detail;
- The process description axis of the PPMX matrix has been further expanded to form the Production Classification System (PCS) cube (Schmitt *et al*, 1985). The axes of the cube have been defined as routing restrictions, production rate uniformity (paced or not) and task divisibility (fixed or resource dependent task times). See figure 2.3.

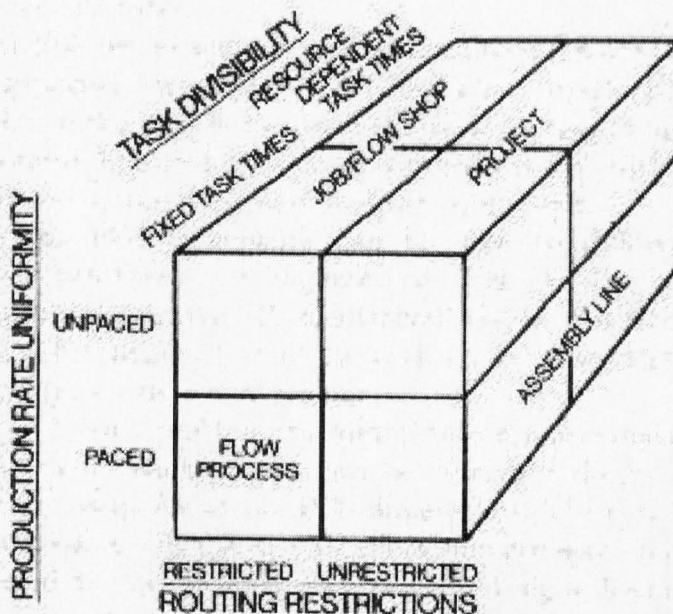


Figure 2.3 – The Production Classification System cube (Schmitt *et al*, 1985)

PPMX has also been developed (Ahmad and Schroeder, 2002) to include a measure of fitness of the organisations populating the product space of the two original axes (their ability to minimise some of the tradeoffs of flexibility for flow implied by the matrix). This can be seen as an addition, following the advent of the best practice and quality movements.

These classification systems are now being superseded by the notion that all manufacturing and business activities can be made to flow. The importance of these frameworks is valid, however, when the axes they have defined are considered.

A flexible plant can be viewed as one that *"can perform comparably well when making any product within a specified range"* (Upton, 1995). A study based on the International Motor Vehicle Programme (IMVP) data set looking at the impact of product variety on plant performance was able to conclude that the lean producers were better able to absorb product related complexity (as expressed as product option variety, option mix and component part complexity). Labour productivity and quality (already identified as being higher in lean plants) were similarly unaffected by the variety in lean plants (MacDuffie *et al*, 1996).

Given this conclusion, flexibility cannot simply be viewed as part of a trade-off with process selection. A definition of flexibility must include the following (Gerwin, 1993):

- It must be applicable across industries. Studies in flexibility have often been specific to one industry. A study of flexibility in Flexible Manufacturing Systems (FMS) recorded eleven measures (Stockton and Bateman, 1995). A study in the paper manufacturing industry used entirely industry-specific process parameters (Upton, 1995). The results of these studies are useful in drivers for that industry and allow theories to be developed (such as Upton's conclusions as to the importance of aligning the measurement, incentives, training, IT to the flexibility strategy and the importance the right type of flexibility for competitive advantage).
- Agreement on the dimensions of flexibility. There is a plethora of definitions of flexibility. A study of small and medium manufacturers based on a level set of seven types of flexibility (Petroni and Bevilacqua, 2002), for example, showed that two "clusters" of

flexibility practice emerged to reflect “mass customisers” (component suppliers competing on cost and volume scalability) and “innovation oriented” Original Equipment Manufacturers (OEM’s) operating in a high degree of market turbulence, competing on new product introduction *etc.* Similarly, other definitions proposed have concentrated on developing hierarchies of sets of facets of flexibility (*e.g.* the shop floor, plant level, business/strategic capabilities).

This can also be viewed as part of the strategy making process (Gerwin, 1993) of having reactive or proactive approaches to developing a response to market uncertainty.

The trade-off implied by the PPMX between process structure and the flexibility available from a manufacturing system is not robust. A contributory factor to the lack of clarity in this subject is that flexibility itself lacks a universal definition. However, using the evidence and definitions available, it is appropriate that the impact of best practice and world-class manufacturing can now be considered.

The entire field of study and practice is based on making tradeoffs between utilisation, variety and unit cost. The difficulty in this type of decision-making is self-imposed given the range of constraints imposed. Whilst this coincided with the notion of complexity reduction in the organisation, there is little evidence of a widespread complex systems view of the company (this will be returned to in section 3.2.2). It will be shown that these constraints are overturned in the paradigm that replaced it, to be discussed in section 2.3)

2.3 The state of the art in “operational effectiveness”

2.3.1 Recognition of the “operationally effective” form

A new paradigm in manufacturing was begun in Japan after World War II. By the late 1970’s onwards, Japanese manufactured goods were introduced to western markets. The substantial price and quality advantages of these goods were brought to the attention of their western competitors. Examples of this are numerous (Abegglen and Stalk, 1985). The resulting set of

practices underpinned by philosophies came to be known as “focussed”, then “lean” and latterly, “world class” manufacturing. This has been restricted almost entirely to the manufacture of discrete piece parts and their assembly into complex products. Process industries (while they have adopted many unitary best practices from the published set of tools) are already based on balanced flows. The performance gap between the West and Japan does not exist in the extreme that has been seen in industries where more design choice exists in how complexity can be managed in the pursuit of operational excellence.

The first exploration of the reasons for the performance gap was made by Richard Schonberger, who published a definitive work on the role of simplicity in nine aspects of Japanese production systems (Schonberger, 1982). Quantitative studies followed of the effects of lean production on plant performance have been conducted and the results are well known. To summarise them briefly:

- The International Motor Vehicle Program (IMVP) study conducted by MIT (Womack *et al*, 1990) identified the astonishing performance gap between lean and mass producers. Quality, direct labour hours per vehicle, inventory in the value stream and years per new vehicle development all showed at least a factor of two leadership by lean producers over their mass production competitors (Womack *et al*, 1990). The ability of lean producers to attain a more flexible response from a plant without compromising other aspects of performance was also found in the IMVP data (MacDuffie *et al*, 1996);
- The Andersen Consulting Lean Enterprise report (Andersen Consulting, 1993) shows similar results in labour productivity in European suppliers of automotive brakes, seats and exhausts as seen in vehicle assembly in the IMVP study. The study reported on World Class (low defects in parts per million and with high labour productivity) and non World Class plants;
- A study by McKinsey & Company (Rommel *et al*, 1996) found that companies with commitment to a Japanese quality culture and practices had substantially higher return on sales and normally at least twice the sales growth of lower quality companies. Four distinct classes of company were identified (in order of increasing quality sophistication and financial performance): Inspection; Quality Assurance; Prevention and Perfection;

- A study of the financial performance of UK lean and other producers (Oliver and Hunter, 1994) also showed higher sales per employee and more rapid growth in lean producers. Interestingly, their research also showed that in the recession-bound UK (1991-2), lean producers appeared to be more fragile than their competitors, with the downturn affecting profitability more heavily.

The measurement of leanness has been important both in recognition of the gap produced between Japan and Europe/North America, and in the ongoing transition of traditional manufacturing operations to “operationally effective” or World Class. Several tools have been developed to capture the dimensions of leanness (Hines and Rich, 1997; Hines *et al*, 2000) and then use the measurement to target systemic improvement. The basis for the measures is time-based (measured as inventory, demand amplification or a decision point between being able to pull or having to push inventory in a value stream) or quality based (measured in defects). This is diametrically opposed to the systems evolved before the Japanese paradigm was recognised. Lead-time was an outcome from a degree of loading on resources that were sized by economies of scales and lot sizing equations. The benefits of being able to pull rather than push inventory was not recognised, and were certainly not sought after.

2.3.2 Anatomy of “operational effectiveness”

Manufacturing exists to deliver Value

The first difference between the western and Japanese forms is the external environmental focus of operations, and the total influence this has on the form that follows this function. The focus on the customer for the manufacturing activities is the only constraint imposed on the system.

The definition of what is valuable in the operationally effective organisation is extremely important. Conventional lean literature (Liker, 2001) asserts that all activity and resource in a system can be categorised into one of the following: Value Adding (VA) meaning that the customer should be prepared to pay for the activity; Non Value Adding (NVA) meaning that they should not, and Necessary Non Value Adding (NNVA) meaning that the activity adds no value but

is necessary in the paradigm faced by the producer. The definition for value proposed by Goldratt and Fox (1986) (*i.e.* that value only emerges in the completion of a process and the sale of a product to a customer) overcome some of the shortcomings of the VA/NVA/NNVA framework. These shortcomings are that VA/NVA/NNVA can only be applied in appraising the activities of an existing process and is a relative measurement only.

This view of value has recently expanded by Murman *et al*/(2002) in the Lean Aerospace Initiative (LAI) to apply value to all stakeholders (rather than just customers) in a process. They also propose a set of guiding activities for the creation of new flows (military aviation projects) to assist with the identification, proposition and delivery of value.

The flip side of value is waste, and to help identify value, a lot of work has also been done in identifying waste. Perspectives on waste are given as follows in Figure 2.4

Monden (1993)	Ohno (Liker, 2004)	Liker (2004)
1. Excessive production resources 2. Overproduction 3. Excessive inventory 4. Unnecessary capital investment	1. Overproduction – producing items for which there are no orders; 2. Waiting time by operators; 3. Unnecessary transporting of work in progress; 4. Over processing or incorrect processing of parts; 5. Excess inventory; 6. Unnecessary movement by operators; 7. Defects and scrap.	In addition to the seven wastes of Ohno: 8. Wasting people’s potential and wish to contribute creatively to their work

Figure 2.4 – Waste in production systems

Creating a Flow of Value to Customers

A breakthrough in understanding the importance of flow in manufacturing processes came from the insight of Israeli physicist Eli Goldratt that the bottleneck process in a factory is the limiting factor in the effective flow rate of a process. By controlling the flow through a bottleneck

resource or process step, then entire process may be controlled. By extension, only the flow through the bottleneck needs to be optimised and protected with buffering. Similarly, material release and scheduling for an entire process may be optimised by careful attention to the flow at the bottleneck.

This realisation that regardless of organisational form, that flow through capacity constrained resources (CCR's) was critical but largely neglected, led to the development of Optimised Production Technology (OPT). OPT aims to control processes around the bottleneck resource (Goldratt and Fox, 1986; Goldratt and Cox 1984). This was in turn developed into replacement automation products to support an improved flow regime and simplified operations (Franks and Keith 1995).

Components parts to enable flow

The driver behind lean production is the flow of value to customers. It is a highly interconnected framework of tools and techniques, and much study has been diverted to separating the tools for unitary study. The result has been the loss of the whole, which remains simple and elegant. This whole has only recently been defined in academic literature.

The classification for these tools has often been conceptualised as a set of tools to remove waste from the system (figure 2.5).

Set of tools	Evidence
<p>Genba Kanri leadership in the process views <i>kaizen</i> (high frequency, high volume process based improvement) as part of a continuum that includes business re-engineering and technological innovation. The success of Genba Kanri is the role of the first line manager (FLM) around whom a further six practices are fostered:</p> <ul style="list-style-type: none"> ▪ The standard operation; ▪ Identification and removal of waste; ▪ Downstream customer focus; ▪ Real operational teamwork; ▪ Team-based performance measures; ▪ Fast-loop performance feedback and learning 	<p>Handyside (1997)</p>

<p>The Toyota Production System comprises:</p> <ul style="list-style-type: none"> ▪ Kanban system with information transmitted via Kanban; ▪ Standardisation of operations; ▪ Process layout for shortened lead times; ▪ Shortening set-up times; ▪ Production smoothing (heijunka) via demand management; ▪ Autonomation (Jidoka) – human friendly, poka yoke, automation; ▪ Quality improvement activities 	Monden (1993)
<p>Focus on Quality, Cost, Delivery. Emphasis of supervisors and workers is the standardization of work (maintenance) and sponsoring continuous improvement (kaizen) through a deceptively simple credo:</p> <ul style="list-style-type: none"> ▪ Focus on the Process versus the result; ▪ Following the PDCA/SDCA cycles; ▪ Putting quality first; ▪ Speak with data; ▪ The next process downstream is the customer. 	Imai (1997)
<p>Total Quality Control leading to Zero Quality Control (100% free inspection of parts made in capable processes). They argue the fundamental difference of the Japanese approach is the management of the process, not management by results/outcomes, supported by statistical process control and poka yoke mistake-proofing.</p>	<p>Ishikawa (1985)</p> <p>Imai (1986)</p> <p>Hirano (1987)</p>
<p>Six sigma is a process improvement project framework based on the notion of mutual value entitlement of a supplier and their customer, to be achieved through high quality, which in turn delivers the lowest costs.</p>	Harry and Schroeder (2000)
<p>Work standardisation and flow cell implementation through a prescriptive process and set of rules for cell design</p>	Rother and Shook (1999)
<p>Theory of small machines - right-sized production processes supporting single piece flow in cells</p>	Bicheno (2000)
<p>Standardisation is a key tool. An Ascendant Organisation is one in which two separate axes are maximised – control over processes and commitment of people. This unites two fields of study, industrial engineering and behavioural social sciences. The standard operation is an example of this – it implies high process control (Taylorism) and can be used with continuous development of people. The method used at Nissan is the "ILUD" system for progression within a standard operation from achieving the correct quality (in the takt time) to being able to teach others and improve the operation.</p>	Wickens (1995)

Figure 2.5 – Lean tools to eliminate waste

Leaving the parts of leanness presented as a set of tools has been frequently, and (in the opinion of the researcher) erroneously carried out. It is in their whole that a property of leanness emerges. As such, this form of literature on leanness and “operational effectiveness” can only be described as incomplete rather than contradictory, and the tools presented are well understood. The only area where there is disagreement over the tools is Six Sigma, which is criticised (Murman *et al*, 2002) for its project focus (sub-optimising the whole process). This is a criticism of the choice of use of the tools rather than the tools themselves. The perspective of the whole system rather than the unit activity is a theme in lean literature, and its implications will be discussed in Chapter 9 in research question 7.

Synthesis of the conventional view of “operational effectiveness”

The synthesis of the parts has been referred to as simplification (Schonberger, 1982) and is evidenced as a self-reinforcing improvement cycle in figure 2.6. Hayes *et al* (1988) talk about focus. Barker (1994a; 1994b) gives examples of a production cell that underwent a transformation and attained the sort of improvements identified in section 2.3.1.

Costanza (1996) extends the use of the tools further, as Demand Flow Technology (DFT). DFT goes beyond transformations to in-house manufacturing and purchasing activities, to include upstream and downstream activities. DFT looks at the implementation of engineering change, structuring of bills of material/manufacture and the ownership of finished good inventories after a DFT project when new flow-based systems are in operation.

Schonberger (1986; 1996) has broadened the concept of lean production as a class of distinct “Japanese” practices and re-established a link to competitive strategy through the “World Class Manufacturing” concept. The manufacturing organisation now delivers Value at world-class levels of Quality, Speed and Flexibility. Lean tools are key to this more global objective. As guiding principles for the modern manufacturing manager, he has published an action agenda for manufacturing excellence in the form of a seventeen-point plan. Interestingly, this plan is

completely free of the detailed use of tools seen in most other literature on leanness and excellence.

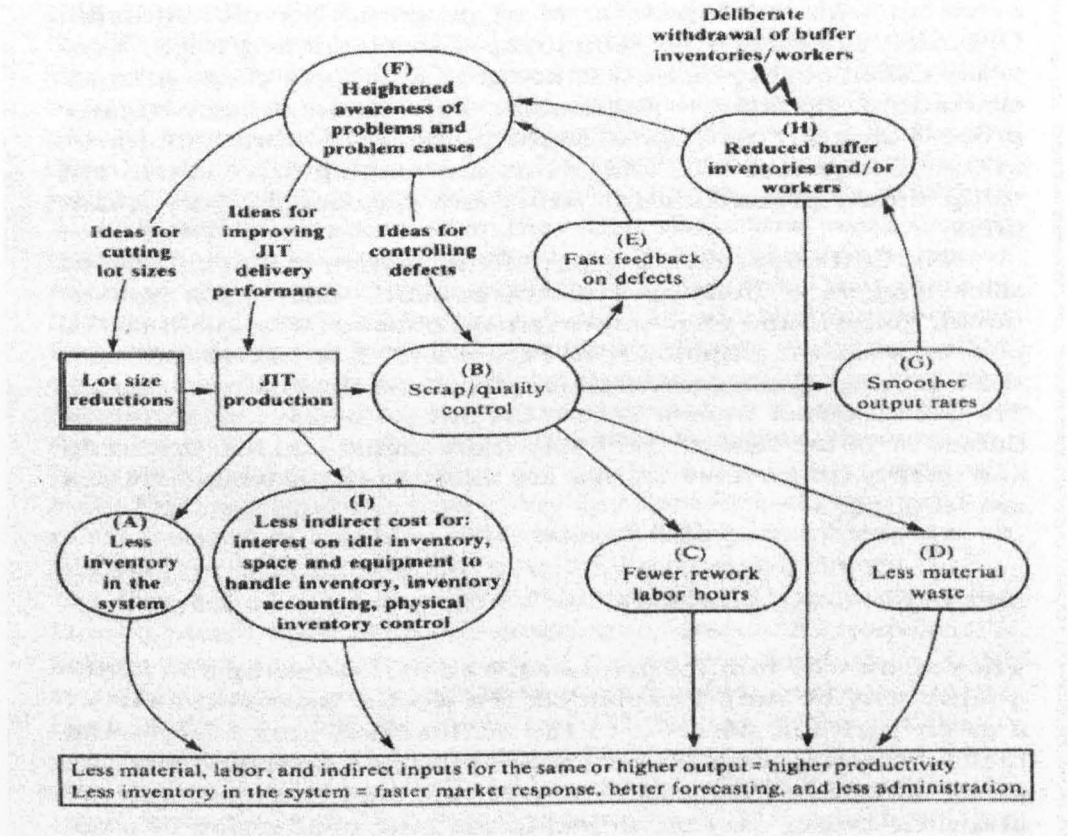


Figure 2-6. Effects of Just In Time Production (Schonberger, 1982, p26)

Another explicit link back to business strategy from the pool of best practices in lean and World Class Manufacturing is “enlightened manufacturing” (Brown, 2000). This is underpinned by a strategic, focussed and holistic view of manufacturing, seen as customer satisfaction achieved through quality, innovation and flexibility. Strategic management of process technology, Human Resources and inventory (through partnerships) provide performance in quality, innovation and flexibility. It is also worth noting that the leanness described in this section focusses on a “one best way” and in doing so, negates a great deal of the product space of the PCS cube discussed in figure 2.3.

This view of leanness as a process or journey to world-class has overcome some of the fuzziness and lack of clarity evidenced by lists of tools and techniques. More recently, attention has turned more to what these systems are trying to achieve and the rationale for excellence the use of

these tools are supporting. Liker (2004) and Spear and Bowen (1999) have been particularly noteworthy.

This leads to the search for an explicit definition for “operational effectiveness” or leanness. A study of the “DNA” of the Toyota Production System (Spear and Bowen, 1999) was able to produce a distillate of four short rules for fundamental process design:

- Highly specified work activities;
- Direct connections between supplier and customer;
- Unambiguous yes/no mechanisms for communications between supplier and customer;
- Changes in accordance with scientific methods and implemented as low as possible in the organisation.

A similar, expanded set (also encompassing softer, people issues) has been proposed, based on fourteen points (Liker, 2004). The starting point for this work has been that Shingijitsu / Toyota Supplier Support Centre consultants have visited established lean producers and rapidly produced improvements of a similar order to those achieved in the original lean transition project. This was discussed in the introduction in Chapter 1.

Both the four rules of the “DNA” and the fourteen principles of “The Toyota Way” have been extensively tested by their authors, with examples from across the organisation. Given the simplicity of what is proposed, both researchers point to a potential explanation as to why some lean adopters are able to go wrong. They attribute this to a focus on the tangible paraphernalia, *i.e.* the tools and techniques. Liker calls this the difference between the Toyota Way and the Toyota Production System (TPS). Spear and Bowen also discuss that the use of kanbans and other tools are purely contingent on their suitability to solve a problem in order to be consistent with their four rules.

This conclusion has been verified by a survey of the lean literature, none of which has offered a crisp definition of leanness (and by implication “operational effectiveness”) until recently.

2.3.3 Adopting “operational effectiveness”

Preparing the organisation and running the change project to embrace lean production has been extensively studied (Liker, 1998). This includes the need for a single programme, (inclusion of everyone in the organisation) and caveats the substitution of training (while essential preparation) for leadership in projects. The conclusion that an organisation cannot “Kaizen blitz” its way to leanness is also drawn. The study included the manufacture of numerous automotive suppliers, medical filters and wooden garden products. Little is said about these companies’ experiences of an explicit sequence of implementation, however.

Mould and King (1995) also studied implementations in the Scottish electronics industry and found that no patterns of behaviour or evidence to support formal models. They looked at the uptake of discrete practices, and interviewed senior managers to get their views. This research also lacked an underpinning framework for the discrete practices. There is no evidence of any synthesis of these practices into an emergent whole, or recognition as to why these practices are pursued. This is the worst example that was found of reductionism in the study of lean production – formal models even as null hypothesis being completely ignored.

The sequence of implementation activities is clearly of high importance, and experiences differ. Clearly, the identification of value will direct all subsequent activities, and is an important defining step. It is in the actual value delivery (Murman *et al*, 2002) or flow/pull/perfection steps (Womack and Jones, 1996) that differences have been noted. These broad philosophies are in evidence, as shown in figure 2.7.

There does seem to be no one single right way to make the transition to lean production. This does not mean that there are no “definitely wrong” ways to go about the change. The “Kaizen blitz” event was initially a very popular method of introducing lean / world-class practices to new parts of businesses, or to struggling businesses in crisis. Initial results are spectacular but these results are not sustainable (Liker, 2001). A process of transition based on the systematic identification of value (mapping and transformation to an ideal future state) is the emerging “one

right way” as advocated by the Lean Enterprise Institute, building on the work and experiences of Womack and Jones (1996). This is described in detail by Rother and Shook (1999) and Rother and Harris (2001).

Implementation sequence	Evidence
Value Definition-Value Identification-Flow-Pull-Perfection Once value has been defined (requiring some initial quality awareness), this implies reorganisation of flow, inventory control then quality and process improvement in pursuit of perfection	Womack and Jones (1996)
Reduce inventory to expose problems, and pull only what is required from the system. This will expose which quality problems must be addressed first. Flow reorganisation can then follow.	Ruffa and Perezziello (2000)
There is one best way. High performance is a sand cone of practices built on Quality, dependability of the production/delivery system, speed of response can then be increased and finally, cost efficiency achieved.	Ferdows and de Meyer (1990)
The sand cone model is supported by a “rugby ball” correlation shape in the plot of performance against the adoption of practices in the Global Manufacturing Research Group Data. Interestingly, there is often some performance difference for a given set of adopted practices, implying that individuals’ competence in adopting tools and practices is a major factor in determining success.	Corbett and Whybark (2001)
Quality education and programmes first, followed by delayering of vertical organisation structure. This acts as a base (to be supplanted over time by continuous improvement) on which team organisation, pull scheduling and waste reduction can be pursued.	Ahlstrom (1998)
Each companies’ lean adoption trajectory is unique, principally because the uptake of lean practices are dependant on the market context of the firm. Lewis also questions the longer-term competitiveness of the lean producer, but is unable to prove a case for the latter proposition.	Lewis (2000).

Figure 2.7 – Sequences of change for operational effectiveness

2.3.4 “Operational Effectiveness” penetration of manufacturing activities

Design and Development

The use of the lean ideas in the design and development process have been discussed at length, and show that the same principles can be applied to non-repetitive, information-intensive processes with similar results over older paradigms. Figure 2.8 summarises the literature in this area, and demonstrates conclusively that the lean principles are being applied outside of the factory (Womack *et al*, 1990; Sobek *et al*, 1998; Reinertsen, 1997; Cusumano and Nobeoka, 1998).

Lean principle	Manufacturing	Product Development
Flow replacing batching	Set-up time reduction	Yes
Shortest flow distance / focus	Cellular manufacturing (focus)	Project team Co-location
Standardisation	Standard Operations	Design Standards
Genba Kanri leadership	First Line Manager (FLM)	Chief Engineer
Values	Continuous improvement culture	Core technical values from strong technical and project leadership

Figure 2.8 – Lean principles transferring to product development processes

The Process Enterprise

The event of Business Process Re-engineering (BPR) (Hammer and Champy, 1993) promised a “new world of work”, organised around customers, working through cross-functional processes and enabled by a new generation of Information Technology (IT). The traditional task-centred view of management disciplines developed since the inception of professional management was turned through ninety degrees as the flow of customer value across departments replaced the traditional structure. The process orientation aspect of this view was further strengthened by the many positive experiences of organisations adopting this focus, including IBM, American

Standard, Duke Power, Progressive Insurance, Owens Corning and Texas Instruments (Hammer and Stanton, 1999).

The parallels between BPR and the lean movement in manufacturing are striking. Wasteful or incapable processes are highlighted. Non-value adding steps are removed. Orientation by process reduces functional interfaces. The business will only exist if it adds value to its customers (Hammer, 1996). A completely new view of the organisation as a collection of processes was offered, in which traditional departmental centres of skill excellence act as pools of talent to supply processes. A new breed of professional manager, the process owner, leads processes.

This view has now been consolidated into an agenda for business (Hammer, 2001), which retains many similarities to the principles of lean manufacturing, including:

- Focus on the end customer for the product or service – delivering maximum value and becoming *Easy To Do Business With*;
- High performance from processes;
- Measurement of processes to help manage them and align objectives across the business, rather than just account for them;
- Standardised systems for creativity and innovation in the organisation. (Hammer and Stanton, 1999) describe standardisation as the most important issue in process design. It has completely replaced the trade-off of centralised control and decentralisation/autonomy in traditional, departmentalised organisations;
- Integration across organisational boundaries (re-engineering the entire value stream).

This latter point has been reiterated for the advent of the tools now available in the digital economy (the promise of IT first raised in the early literature on re-engineering). X-Engineering (Champy, 2002) discusses three essential ingredients in using the internet and other tools of the digital economy, which are again very similar to the agenda, above. They are Processes (fitness of upstream, downstream and in-house processes), Participation (degree of integration, power sharing *etc.*) with partner organisations and Proposition (value added) to customers. It is obvious that the process enterprise advocated by business process reengineering is a company-wide,

generalised form of lean production practice (usually restricted to the factory floor and its immediate environs).

Quality Management System Standard (ISO9001:2000)

Tricker and Sherring-Lucas (2001) point out that ISO9001:1994 (the previous revision of the standard) focussed on the standardisation of work procedures to produce a consistent and traceable customer related output from organisations. This was based on the prescriptive activity set found in most modern companies. The new standard retains this where appropriate, but requires formal documented procedures for only six specific activities of quality management. The new revision of the standard establishes requirements to map core processes, identify key process indicators, and to undergo formal measurement, analysis and improvement activities, including customer satisfaction. The role of management commitment to comply to the company quality procedures has been replaced by management commitment to set and deliver improvement objectives for the business, including the provision of resources. The objective is to demonstrate customer focus, not repeatable quality.

Summary

There is a predominant view that business is a set of value adding processes, but the influence of the view of the process as a complex system is not widespread in pivotal literature. The crux of much study has been reductionist in nature, leading to a loss of the whole. However, the approach of lean and other world-class manufacturing contributing to "operational effectiveness" is inherently reductionist. The contribution of the concept of flow is pivotal and very useful, as it provides the orientation around processes that create value for customers. The resulting focus on value and waste is also very powerful, but it is the belief of the researcher that it does not account for the emergent property of the process' output.

This is then enabled by a set of tools that create unitary standard operations (building blocks) of standardised, capable, activities. These activities are then assembled into processes using simple coupling rules (identified in the discussion of synthesis). This assumes that lean processes can be

scaled in a linear fashion by strict application of these rules, which does not make allowance for the emergence of complex behaviour. This is the antithesis of a complex systems view of agents.

However, the picture created is not simple. There is one striking similarity between the lean ethos and the complex system. This is the goal searching / hill climbing behaviour of both lean standard operation building blocks undergoing continuous improvement through local "Genba Kanri" leadership and agents undergoing adaptation. These are not widely recognised as agents in a complex system whole.

2.4 Agility: After Lean Manufacturing

Agility is a disparate field of study and does not have a single, solid foundation that lean production is built on. Its study was initiated by a wish to reconcile technology with the next anticipated level of customer and market sophistication, with the creation of an important concept called the Economy of Scope (Pine, 1992).

Agile manufacturing is defined as "*the ability of a company to thrive in a competitive environment of continuous and unanticipated change*" (Kasarda and Rondinelli, 1998). As will be shown in this section, there is active disagreement within the research. Some indicate that it is an extension of lean production. Others take the view that it is updated craft production from the pre-industrial era (before mass production in figure 1.1), enabled by information technology.

The environment of change produces both variety and uncertainty, in a concept referred to as market turbulence (Pine, 1992). The worldview of agile manufacture is that economies of scope may be achieved as a competitive differentiator. The ability to access these economies differs from the economy of scale of traditional mass production. Pine proposes that the aim of this approach is to meet the requirements of individual customers, not mass markets, and to be able to do so at the lowest costs and highest efficiencies. See figure 2.9.

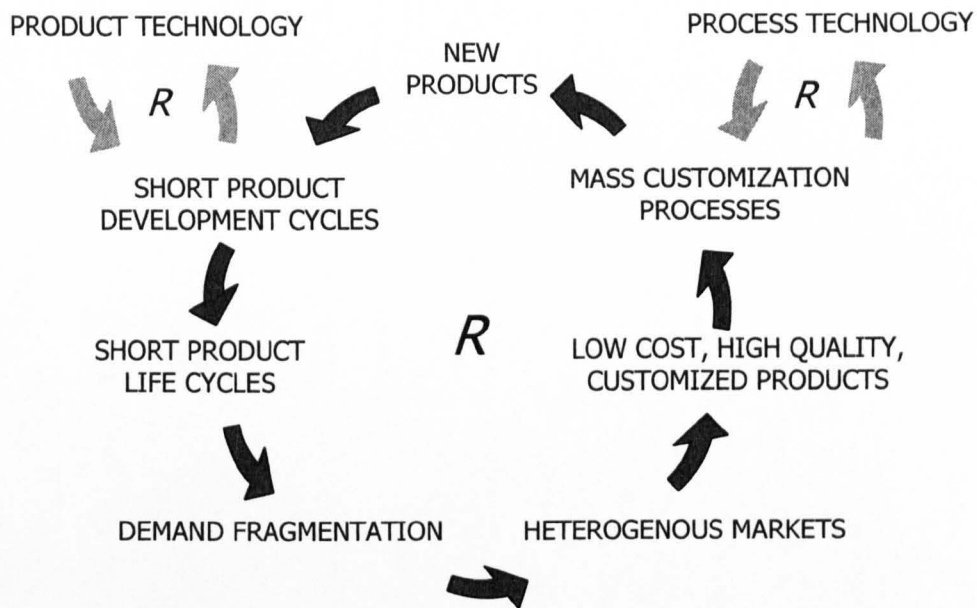


Figure 2.9 Economies of Scope (reproduced from Pine, 1992)

Given this proliferation of product variety and shortening of product life cycles, mass customisation has emerged as a major enabler for agility, based on a Puttick grid of market turbulence vs. rate of change of the process. High market turbulence and low rate of process change lends itself to this approach. Interestingly, the area of low market turbulence and a high rate of process change are viewed as the preserve of continuous improvement.

Pine, (1992) has identified five types of mass customisation:

- *Customise services around standardised products and services;*
- *Create customisable products and services;*
- *Provide point of delivery customisation;*
- *Provide quick response throughout the value chain;*
- *Modularise components to customise end products and services* (six further methods of offering modularity are also discussed).

In this paradigm, the product life cycle is decoupled from the organisation. The organisation is focussed on the life cycle of the process that delivers the products. This is a subtle shift from pure focussed or product family manufacture. This further develops the notion of the value

stream, and the organisations long-term ability to meet a customer requirement, in this case several iterations/cycles in product and process technology.

A similar summary of the evolution of the economy of scope can be found in Kidd (1994). Having established the rationale and background to providing more variety more frequently on a process life cycle, there is a need to discuss the organisation form that will be required to meet this challenge. Kidd defines terms for an organisation form based on equal attention to People, Organisation and Technology. Several design methodologies are then reviewed from software industry, finally summarising the HITOP (High Integration of Technology, Organisation and People) design methodology. Without prejudging the form of these agile organisations, several predictions are made:

- The agile organisation will be a network, rather than a neat flow;
- Reconfigurability will be key. This is supported by Gould (1997);
- The existing "hard" systems view of optimised, closed systems is not appropriate for the HITOP, and with it the principle of reductionism to establish a unit of analysis;
- The sharing, management and mitigation of risk will be critical in the successful operation of these systems.

Goldman *et al* (1995) also view agile manufacturing as a system which cannot have a fixed structure, but should offer competitive differentiation if applied successfully.

Holonics (McHugh *et al*, 1995) is a speciation from Business Process Re-engineering (BPR), because of its adoption of the environmental consideration in how these systems operate. Strategy is not made and deployed explicitly, and instead an agile and 'opportunistic' response is made to environments (markets), with a strategic end game in mind. The characteristics of holonic enterprises and their similarity to complex adaptive systems are discussed in section 3.3.

Schonberger (1996) takes a view more rooted in a strong connection and addition to World Class Manufacturing (WCM). Supporting the idea that process management is the key tool (the one big

idea) amongst the other tools and techniques of lean/WCM, he offers a framework of Quality, Speed, Flexibility and Value to meet the challenge of the economy of scope. He offers sixteen principles to support his vision.

The subject of the synergy or paradigm shift involved with agility is one of the things that have stopped a formal definition being developed. Pine has offered that there are actually two routes into the new competition (Pine 1992), from:

- Leanness;
- Flexible specialisation (the application of the economy of scope to craft production).

This has been explored at length. Two types were found in Japan, in bicycles and air conditioning units (Hanson, 1997). The manufacture of bicycles was also studied by Kotha (1996) at the same firm. He studied the fit between a small, customised process adapted from craft production (exploring market niches) operating alongside a mass production system, with apparent benefits to both processes. The air conditioning units were being made using pre-assembly kitting and flexible assembly practices on a large line, thereby achieving a fully integrated lean "mass-customiser" (Hanson, 1997).

This split between lean and craft origin for agility goes further. (Harrison, 1997) argues that lean and agile production has the same objectives, but that true agility requires more resources (capacity) than would be traditionally associated with a lean producer. He further argues that agility has its origins in jobbing or project management environments (high variety, low volumes), whereas leanness is best practice in low variety, high volume production. This supports his assertion that a trade-off between flexibility and flow is alive and well in manufacturing. This actually contradicts the established "operationally effective" view of the "one best way" of lean production.

Leanness is also viewed as a necessary precedent to agility (Goldman *et al*, 1995; Ashall and Parkinson, 2002), and that the additional requirement of reconfigurability of processes is the principal difference between a lean and agile manufacturer (Gould, 1997).

The role of the customer has been considered to attempt to better understand the types of agile form emerging. Duray (2002) has a matrix of stages of modularity (Design, Fabrication, Assembly and Use) versus the point of customer involvement (Design, Fabrication, Assembly and Delivery). This will affect the nature of variety proliferation and risk mitigation in the total manufacturing process. Further research in this area is focussing on the late or early commitment of customers to specific orders in the producer value stream as a way to reduce reconfiguration costs and upstream disruption when the decision point is very late in a value stream (Brabazon and MacCarthy, 2004).

One common theme in the research is the importance of knowledge management and the Information Technology infrastructure to support the agile producer, whether as a virtual or integrated enterprise (Kotha, 1996; Kidd, 1994; Upton and McAfee, 1996). A further theme is the role of measurement in agility.

Agility appears to be a set of tools and capabilities searching for use in the competitive opportunity presented by market turbulence. It has common elements with lean production and Business Process Re-engineering insofar as it uses flow (processes) extensively, albeit with networks rather than value streams. The continued dominance of lean thinking, however, implies that there is real value in this preceding paradigm, and that Agility will not overturn and challenge it in the same way as lean did to variety mass production. The crux of the argument by the agile community of researchers is that lean production "will not be enough" in anticipated forthcoming market turbulence. This may be true, but it would be difficult to imagine an "operationally effective" organisation form where lean principles were not thoroughly embraced. It must also be concluded that leanness itself is not about the tools used (though it has been shown that there has been great attention to them). Rather, it is the underpinning philosophy of flow, enabled by variation reduction, which allows high quality, low cost and predictable delivery.

Agility can be shown to include some input from complex systems, this being the similarity between the holon and the agent. This is not embedded or exploited extensively as yet.

2.5 Modelling: representation and simulation

A large number of formal methodologies exist for the definition, design and implementation of processes. The software engineering discipline has contributed a large number of these, with the rationale of improved delivery of complex software to requirements, in budget and in time. These methodologies occupy a full spectrum from the traditional (reductionist) decomposing by function through to the abstract orientation by self-contained objects.

Summarising the principal literature on these techniques in both the software and manufacturing systems domains are Wu (1992), Somerville and Sawyer, (1996) and Kotonya and Somerville, (1998) and others. Figure 2.10 shows a summary of the main methodologies, with differing emphasis. It is neither exhaustive nor mutually exclusive. It is approximately chronological in sequence, and shows a shift from functional decomposition to object orientation. See Figure 2.10.

Methodology	Emphasis	Tool
Functional decomposition	Process modelling as the conversion of inputs to outputs by a hierarchy of functions	IDEF ₀ and related process mapping tools (Hunt, 1996)
SADT	Process modelling as the flow of information and decision points	Activity Diagrams – DFD’s with control details
GRAI	Process modelling as the synthesis of decisions and operations	GRAInet & Grille d’Analyse
SSADM	Flow of data through a process	Data Flow diagram (DFD)
Semantic modelling	Classification of model entities	Entity Relation Modelling (ERM)
Object Orientation	Entity composition – hierarchical (inheritance) classification with attributes	HOOMA, Booch, OMT, OOA, DOORS, UML now prevalent
	Process modelling – hierarchical classification of use cases of entities	UML

Figure 2.10 – Summary of representation methods

The current state of the art is the introduction of the Unified Modelling Language (UML). The UML tool is a set of nine static (four) and behaviour (five) modelling systems (diagrams) that share the same sets of parts, which when used consistently build a total picture, from business context to data structure and conditional object states (Holt, 2001).

GRAI is unique in its dual representation of processes as interconnected decision points in the context of timeframes for both a planning horizon and the period (cycle) of decision making events. Examples of its use include mapping complex production Planning, Scheduling and Control (PSC) problems (MacCarthy *et al*, 2002).

The common and highly important strands to all of these techniques are the core building block of a transformation/function/operation, system entities in hierarchies (implying some structure or organisation, including the resources required to carry them out), and the existence of control/decision points. In summary, two general categories of process mapping exist:

- The hierarchy of a subdivided flow of functions to convert inputs to output using mapped resource entities. Examples of the use of this include the generic Order Handling Manufacturing System (OHMS), based on one of Wild's four manufacturing archetypes (Wu, 1992), and in the mapping of processes described in Hunt (1996);
- Hierarchical classifications of data entities, performing operations (or functions) in a similar hierarchy of use cases. An example of this is the Manufacturing Data Model (Langer and Alting, 2000).

Turning to simulation modelling and experimentation with these descriptions of real world systems, both types of technique are evident and in use. In common (irrespective of how it is used) is the building block of the entity itself.

Simulation has a number of advantages over other forms of experimentation. It allows the study of systems (Robinson, 1994):

- In non-nominal, non-steady state behaviour;
- With non-standard distributions, allowing interactions of randomness;
- As a total solution that can be tested;
- As highly effective communication tools.

Three broad classes of simulation exist:

- The first type is a top-down, continuous systems dynamics model (based on control and feedback loops). Functions are deterministic and can be time-sliced;
- Top-down discrete event models are based on time indices of events rather than time slices. This model requires an execution engine based on events, activities or processes, or a hybrid of all three. They are valuable as they allow for stochastic interactions *i.e.* dynamic behaviour;
- Bottom-up models of entities, made of active objects (agents). They have rules and work collaboratively / competitively with one another or the environment towards an objective or goal.

The typical steps in a simulation project are summarised in figure 2.11:

Model type	Comment	Source
Discrete Event	Simulation projects require problem definition, model building and validation, experimentation, model completion and implementation	(Robinson, 1994)
All types	Simulation comprises three steps: Modelling, computing, experimentation	(Pidd, 1992)
Agents	<p>Melanie Mitchell has defined six steps to creating an agent-based simulation:</p> <ul style="list-style-type: none"> ▪ Simplify the real world problem to a minimum set; ▪ Develop the software for the individual agents and their rules; ▪ Run the programme with different starting and statistical effects, and summarise resulting behaviour; ▪ Try to understand how each agent’s simple rules give rise to the complex behaviour of the entire system; ▪ Change system parameters to test your understanding of the actions of agents and their rules; ▪ Further simplify the simulation (or add other factors) to produce the complex global behaviour of interest. 	(Casti, 1997)

Figure 2.11 – Modelling summarised

This shows that there are common strands to every method. Model validation is also critical in all forms of simulation. It has the goals of eliminating three forms of error (Pidd, 1992), the latter two of which are common to statistical hypothesis testing:

- Type 0 – the wrong problem has been defined and answered;
- Type 1 – a correct hypothesis has been rejected by a false result;
- Type 2 – a false hypothesis has been accepted by a false result.

Two forms of validation exist. Black box validation confirms that for a given input data set, an expected outcome results set is produced. The internal working of the model is invisible. White box validation seeks to establish transparent, accurate behaviour from the model mechanisms, *i.e.* that an accurate model is being constructed.

Sensitivity to initial model conditions, taken as a measure of repeatability, is also critical in comparing the model and the reality being modelled. It is also important that a desired range of model parameter space can be explored in both model (of reality) and in the scope of experiments.

In all of these issues, the discrete event model is of particular interest because:

- It uses entities of various forms;
- Each resource type entity has an observable event state from a finite set, and serves a queue;
- It is constructed to represent functions as activities in a process;
- Each resource entity acts as part of a connected network of resources serving their queues.

This framework supports both the mapping and simulation/experimentation aspects of modelling. It also provides a framework to allow a measure for complexity, discussed in the next chapter.

2.6 Conclusions

In this chapter it has been possible to show that operational effectiveness and how it is currently measured are not influenced or informed by complexity science. This has been done through a survey of what operational effectiveness aims to be and hence achieve by contributing a differentiated manufacturing capability to a strategic position in a market, and how effective performance is currently measured. The precursors of the current view were also investigated and whilst an interest in complexity reduction was found in this research, it was in dealing with complexity generated from internal constraints of this earlier paradigm. The new paradigm can be shown to be fundamentally different, with the concept of a trade-off replaced by a “one best way” of good practices. When this paradigm was explored at length, a reductionist rather than complex systems worldview was found. This pertains to both how “operational effectiveness” has been understood and also to the fundamental paradigm in operation.

Section 2.4 showed that a newer set of ideas are undergoing development around a common theme of increased market turbulence and exploiting a competitive position from economies of scope (*i.e.* being able to compete and thrive on variety and uncertainty) but as yet do not have the iconic example of an agile practitioner. Nor is there a definitive form for this agile organisation, models being split between a super-responsive lean producer and the updated craft producer who leverages information technology in place of lean practices. This is not enough to displace or supersede the continued cardinality of the various forms of “operational effectiveness” in place as lean manufacturing, Business Process Reengineering or six-sigma quality.

Finally, a survey of modelling as system description and simulation was carried out. There is more influence here from complexity in the form of agent based simulation, and these ideas are well accepted within the discipline but not extensively in the greater manufacturing research or practitioner communities. The external influence of this modelling is not in evidence broader literature.

Based on these conclusions, this survey can be shown to refute the null hypothesis of the thesis, because complex systems have not been readily embraced into this worldview, rendering it unlikely that the complex system view will have no contribution to make to our understanding of manufacturing systems. To explore this further, in Chapter 3 the complex system will be introduced and ideas of relevance to manufacturing will be identified. The impact of the more relevant ideas in complex systems (including their measurement) will then be investigated and it will be further found that complex systems have had limited direct application into manufacturing from within the complexity literature.

CHAPTER 3 - COMPLEXITY AS A NEW PARADIGM IN MANUFACTURING MANAGEMENT AND ORGANISATION

3.1 Introduction to complexity and the study of complex systems

This chapter will provide a summary of the literature on complexity; thereby showing which specific aspects of complexity are of interest to this thesis topic. In doing so it will conclude research questions 1 and 2, about the linkage and cross fertilisation of complexity science into conventional "operational effectiveness" literature (and vice versa), and that there is new material on "operational effectiveness" in the complexity literature.

The remainder of this section will introduce the complex system, and section 3.2 will focus on four areas of interest. Section 3.3 takes the complex adaptive system as the synthesis of these powerful ideas and looks at its adoption into manufacturing systems, principally in the Holonic manufacturing concept, paralleling various systems description and modelling developments from chapter 2. Section 3.4 then summarises the application of complexity science in the pursuit of "operational effectiveness", concluding that it has been restricted to three areas on the periphery of the field. Measurement of complex systems is then considered in some depth in section 3.5. Finally, the chapter is summarised and conclusions drawn in section 3.6.

In representing the real world for any form of hypothesis forming and validation, the process of deduction / induction is a well-established framework (Casti, 1991), shown in figure 3.1.

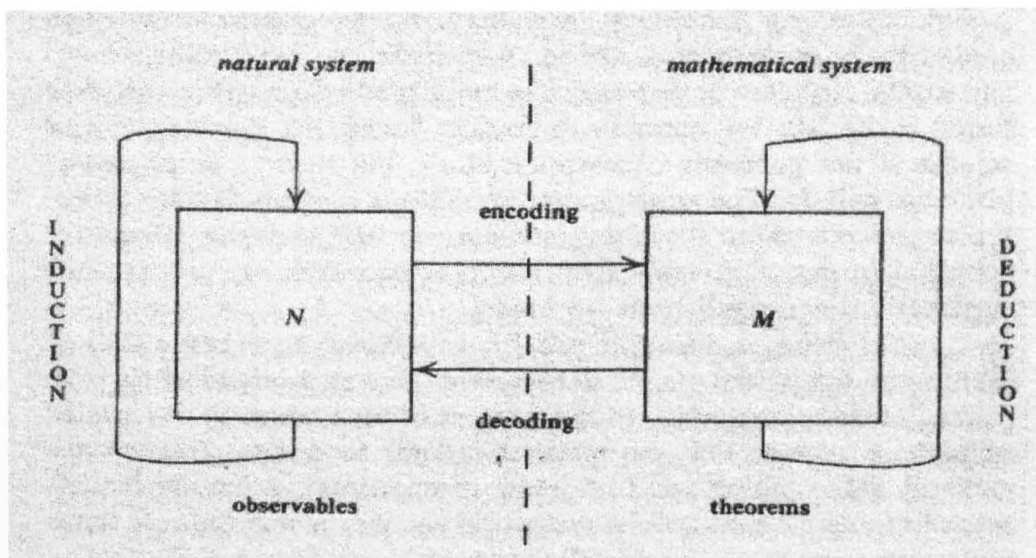


Figure 3.1 – Induction and deduction in model making (Casti, 1991, p32)

The view taken of the different paradigms (from physical science based reductionism, the biological and management sciences and through to complexity science) reveals that there is a fundamentally different view of the world taken in the complexity sciences (Stacey *et al*, 2000). With this accepted, it is possible to challenge the reductionism and closed systems theory of the physical sciences, which rely on the following underpinning:

- It is possible to divide a large, complicated entity into its smaller, simpler parts with no loss of information or descriptive value. This aids the external observer's understanding without any penalty to the validity of the observation;
- The Entropy of a closed system will always increase to a maximum. Any local or global reduction of this must be externally instigated with work from outside the system;
- The system tends to and seeks to be in an equilibrium state. This property allows it to be predictable and controlled;
- It is possible to aggregate large amounts of information or large numbers of entities into a super set, about which behaviour may be approximated (with no surprises);
- Similarly, behaviour may always be predicted from a system's starting conditions and a deterministic rule for its description.

Casti (1994) bases his framework for complexity on the exhibition of a “science of surprises”, and counterintuitive behaviours from systems, namely, emergence, sensitivity to initial conditions, catastrophes resulting from small changes *etc.*

Systems theory, systems (non-linear) dynamics and their synthesis into the study area of complex systems challenges the reductionist view because they embrace the concept that systems are actually open, and may not be reduced for simple analysis. Furthermore, the interactions between system entities are the very source of richness that makes systems complex and hence interesting to study (Flood & Carson, 1993).

The study of complex systems is very large, and the literature search in this chapter has concentrated on the following, as will be discussed in the remaining sections of this chapter:

- 3.2.1 Information and control theories have provided the vocabulary for the mechanics and description of complexity through Entropy;
- 3.2.2 General Systems Theory (von Bertalaffny, 1971) applied in the form of Cybernetics and the Viable System Model (Beer, 1985) have used both information and control as extensions to reductionism. It also introduced the concepts of disturbance and the active role of the environment on every system;
- 3.2.3 Study of connectedness in the form of logic / Boolean networks shows the emergence of order and catastrophic events in apparently random systems. This demonstrates that critical coupling relationship exist and contribute to complexity;
- 3.2.4 Chaotic systems are a special case of non-linear dynamical systems. They provide the generating conditions and exhibit the behaviours associated with chaos and complexity.

The complex adaptive system as the current state of the art for the study of systems will then be reviewed in section 3.3, with reference to the manufacturing systems adoption of this model in holonics. Section 3.4 will then look at how complexity has thus far been applied to the field of manufacturing. One particular application of complex systems measurements will then be reviewed in section 3.5. Conclusions will be drawn in section 3.6.

Drawing on each of these, complex systems as viewed in their current form contain some or all of the following characteristics. This list is neither exhaustive nor mutually exclusive. It appears that complexity lives up to its reputation and remains as difficult to define as actually understand and exploit. It may be easier to show what these systems are not; *i.e.* the reductionist, closed systems described above:

- Complex systems are typically the behaviour of a number of autonomous agents, which are connected in particular ways by rule-based interactions. Just as readily, there are examples of complexity (chaos) that may be generated in the phase space of differential equations;
- They have emergent properties and (as a consequence) are computationally irreducible;
- The systems are open to their environments and as a result, equilibrium is seldom achieved;
- They are self organising, self recreating (autopoietic) and their members co-evolve with one another and their environment;
- Their behaviour may be unstable and cannot be aggregated or necessarily predicted. The outcome of small disturbances from a known point cannot be estimated in the same way that it can be in linear calculus.

3.2 Areas of study of complex systems

3.2.1 Entropy

A particular form of complexity is rooted in control theory and information theory. The concept of Entropy is central to information theory (Cover and Thomas, 1991), a measure for the degree of uncertainty of a random variable. Entropy is useful for a number of reasons. As a measure, it is determined by the probabilities, not the values taken by the random variable. Entropy also provides an equivalent ultimate measure of ultimate data compressibility (equivalent to Kolmogorov complexity), *i.e.* programme length to print the string of data in question, and complements computational complexity (programme run time). It can also be used to explore the coupling between random variables using the concepts of

- Conditional entropy (the entropy of a random variable given a separate random variable);
- Mutual information (the reduction in entropy in one random variable thanks to this dependence on another);
- Relative entropy (the Kullback Liebler distance between two probability density functions of two variables).

The normal use of these concepts is in communications theory. In this context there is a sender and receiver, connected by a channel. The channel capacity is the maximum value of the Mutual information between two random variables (input and output). The whole family related of properties is summarised in figure 3.2.

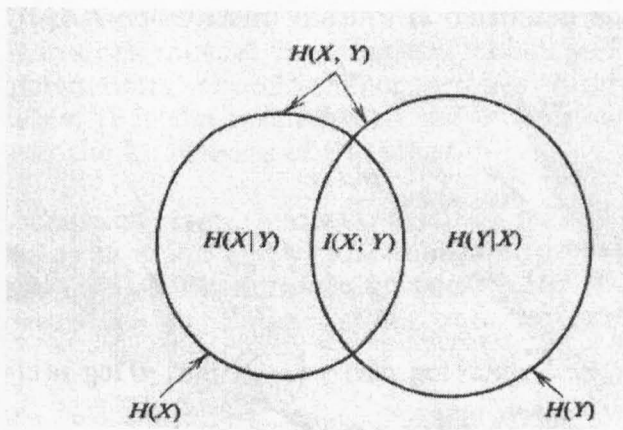


Figure 3.2 - Forms of Entropy (Cover and Thomas, 1991, p20)

Control theory makes an important contribution and there have been attempts to explain the complex behaviour of supply chains in its entirety using control systems theory, principally through cascaded feedback mechanisms (Riddalls and Bennett, 1999). The assertion that has been made is that it is possible to tune supply chain processes and control mechanisms to damp any disturbance.

3.2.2 Cybernetics

A related field to control, cybernetics, is defined as "*The science of control and communication in the animal and machine*" (Robb, 1984). Cybernetics was established from biology to apply the

principles of systems theory with the key concepts communication bandwidth (requisite variety) and feedback control to the maintenance of homeostasis of complex systems. (Ashby, 1956; Wiener, 1962; Varela, 1979). The management of variety (expressed as information for transmission in communications) is the key concept in cybernetics. Variety is managed by establishing requisite variety in both processes and communication between them. Variety may be amplified and attenuated, sometimes usefully, sometimes not.

The most widespread application of cybernetics to management of systems (and latterly to processes) came in the form of the Viable Systems Model (VSM), devised by Stafford Beer (Beer, 1985). The VSM models its control behaviour on the hierarchy of five subsystems, all of which are required to ensure viability. System 1 and 2 are the operational unit and its control respectively. This is then connected to components 3 (the self organisation and regulation of the whole of the units), 4 (self reference in its environment, intelligence gathering, simulation and planning) and 5 (policy setting).

The system described above may be abstracted into an environment (the environment outside of the firm), subsystems 1 and 2, (the operational unit) and 3, 4 and 5 (the managerial unit). One of the principles of good design of organisations is that all three should have the same requisite variety, and that the connecting channels should have an excess capacity over and above this variety.

Each system may be viewed in a recursive hierarchy (of nested sub and super systems), with the system under study being the system termed *in focus*. Its validity as a tool and catalyst to augment organisational designs has been explored and confirmed (Robb, 1984; Schwaniger, 1990). An implication of the nature of recursion is the conclusion that recursion will only take place when a subsystem of a viable system is itself viable (Beer, 1985).

The application of the VSM has been widespread, and includes a tourist enterprise (Flood and Zambuni, 1990) and other manufacturing examples ranging from a small engineering firm to a large paper producer (Espejo and Harnden, 1989). Waelchi (1989), writing in Espejo and Harden

(1989), has expressed the key management paradigms in cybernetic terms. He has concluded that just as Taylor/Fayol were focussed on situational variety reduction and closed systems, then the contemporary (at the time of his writing) excellence movement of Peters and Waterman (1982) focuses on inclusion of the real world (customer, more turbulent markets *etc.*) and the adaptation of the organisation using variety amplification.

The VSM is extremely important because it sets out the roles of parts of an organisation, and employs a measure applicable to for their effective operation – variety expressed as information.

3.2.3 Connectedness

Interactions and connectedness have long been understood to be a source of complexity and richness in systems. As such they have been a focal point in architectural town planning (Alexander, 1964). More recently, Senge (1990) has studied the concept of how entities in a system interact (again using aspects of control theory). This branch of systems dynamics uses a common set of systems “archetypes” as building block patterns of behaviour (Senge, 1990). The examples used in this work are arms races and policy failures (encouraging the sort of behaviour attempted to be deterred), and demand amplification in supply chains (the famous “beer game”). Senge argues that identifying and modifying destructive systems at the point of highest leverage can make important improvements to systems.

Another facet of the interconnectedness of entities in systems is studied in “small world theory”, which pertains to the disproportionate influence that a small number of random connections can have in regular networks in increasing the transmission through them (Matthews, 1999; Barabasi, 2003).

3.2.4 Chaotic Systems

A dynamical system is one that allows deterministic prescription of its states as it goes forward in time. Where N autonomous (time independent) first order differential equations describe a

system, an N-dimensional phase space is created, in which there is a path (or flow) of vectors evolving over time.

This flow can be conservative of volume over its flow (such as Hamiltonian systems which describe idealised pendulums, motion of planetary bodies *etc.*), or it can be dissipative. In a dissipative system there is a reduction of phase space volume signifying the operation of some friction or damping (Ott, 1993).

Both of these types of system can exhibit chaotic behaviour, subject to parameter and initial condition selection. The general condition for the onset of chaos is that the dimension of the phase space is such that $N \geq 3$. This is elaborated upon by the Poincaré-Bendixon theorem which states that for a 2 dimensional phase plane, a flow path must either approach a fixed point, return to its starting position on a closed curve or approach a limit cycle. A phase path can only cross itself at an equilibrium point, and this rules out chaotic oscillation at a dimension of $N = 2$ or less (Acheson, 1997).

The use of maps within the phase space provides insight into the systems under study, since time (one of the dimensions) is removed from the phase space. A Poincaré map is a surface within the space of $N-1$ dimensions, for an N dimension phase space. Other maps such as the time T map work in the same number of dimensions as the space in question. Their purpose is to allow phase spaces to be studied as discrete time systems. Where a map is invertible, every point can be uniquely derived from a preceding point. The simplest illustration is the 1-dimensional map logistic map. For maps, chaos is possible in maps of dimensions of $N \geq 2$. If however, the flow on the map is not non-invertible *i.e.* a single point may have many precedents from which it may be derived, then chaos may be possible at map dimension of $N=1$. The logistic map is an example of this latter form (Ott, 1993).

These convergent paths are found in dissipative systems and are called attractors. The dimension of an attractor is of interest. Coinciding with phase spaces of dimension $N \geq 3$, a further type of attractor called a strange attractor can be found. This is not unlike a limit cycle,

but an irregular oscillation is observed, which does not repeat itself. The strange attractor has a dimension that is not an integer, unlike the other attractors described. The dimension is the ratio of log of number of cubes of length ϵ , to log of $1/\epsilon$, as ϵ tends to zero. Strange attractors gave rise to Mandelbrot's name "fractals" because of their non-integer values.

Strange attractors are often (though not always) chaotic, and chaotic systems do not always have strange attractor geometry. The most relevant and common trait of chaotic systems is their sensitivity dependence to slight changes in their initial conditions. Ruelle (1991) describes how Lorenz has famously demonstrated this in prediction of idealized fluid convection in weather systems. The onset of this divergent behaviour in these oscillating systems caused by parameter variation or sensitivity dependence is often shown by period doubling of the oscillation. Mitchell Feigenbaum (Ruelle, 1991) was the first person to note period doubling whereby a periodic limit cycle orbit is replaced by another orbit that is approximately twice as long.

What is clear from these relatively uncomplicated systems is that unforeseen (far from equilibrium) behaviour may result from small changes to the point in the phase space of the start of the flow, or the parameters determining the flow. These systems are already of interest in many applications in the physical sciences.

3.3 The Complex Adaptive System (CAS) and its adoption in manufacturing

The complex adaptive system is the state of the art in the representation of systems using the complexity viewpoint. Such systems are composed of a small or medium number of autonomous agents, each acting on their own set of rules, in a decentralised, bottom-up hierarchy. This hierarchy lends itself to classification, and is similar to the object-oriented classifications of designed software systems, and Holonic manufacturing processes.

The activities of these agents are via their rules. For an agent-based view of a manufacturing process, this would include the activities resources carry out in processes (both procedural and unofficial). The interaction amongst themselves and with their environment in pursuit of a

measure of fitness competition or co-operation gives rise to the rich and unpredictable behaviour. In pursuit of this fitness (performance), agents also build internal models (Holland, 1995). Where permitted, this will give rise to adaptation, evolution and co-evolution of agents.

The notion of connections (via rule-based interaction) of populations of agents has given rise to the NK-model, whereby critical ratios exist for the average number of connections per node (in this case an agent). Kauffman (1994) also discusses how catastrophic (sudden change) behaviour will be seen which is not seen as slightly smaller or greater values of this ratio, *i.e.* the landscape that this agent occupies is very rugged and prone to sudden changes in optimality of fitness. This interaction gives rises to self-organised criticality. It is also possible for agents to become autocatalytic, whereby the rate of evolution promotes faster and faster adaptation and evolution.

Using the product space occupied by computational (*in silico*) agents (the multi-dimensional space created by the value ranges of the parameters of their rules and operational working), the concept of a fitness landscape also exists, *i.e.* that agents occupy a place on a landscape of performance. The goal of the agent is to achieve peaks of fitness. Agents can then be adapted for optimality by techniques such as genetic algorithms, whereby "fit" agents are bred *i.e.* stochastically recombined and mutated to produce improved variants.

These mechanisms and the results that have been observed from them in a number of fields have provoked much interest. For example, the self-organised criticality of catastrophes manifests itself as a power law such that there is a linear relationship in the log of the size and frequency of catastrophe events. This has been observed in the physical sciences (the sand pile problem) and extinction events in ecology.

Contrasted with the conventional vocabulary and methods of organisation design to carry out certain processes, the complex system (of which the CAS is a form) is very novel. CAS are of interest because they can provide operational effectiveness from simple rules and decentralised (bottom-up) control. This means that they can be flexible, highly responsive, adaptive and innovative without the centralised control that has pervaded science and organisation (Johnson,

2001; Resnick, 1998). The implications for the design and form of manufacturing organisations are potentially enormous.

One of the paradigms for agility involves definition and control of agile manufacturing systems in terms of agents (holons). McHugh *et al* (1995) offer the holonic model as the next step in evolution beyond Business Process Reengineering. A holonic network comprises the following agent-like properties:

- *First, a holonic network is not organized hierarchically.*
- *Second, each holon [is] a business, a switch within the network or a node. In other words, each node is equal to all others.*
- *Third, the network is in dynamic equilibrium.*
- *Fourth, it is self-regulating.*
- *Fifth, access to and exchange of information throughout the network is open, as is access to and exchange of information across the network boundaries.*
- *Sixth the network is evolutionary, and is constantly interacting with its environment.*
- *Seventh, it is a knowledge network, and self-learning.*

This challenges the classical view of all the manufacturing literature of planned or designed responses to a requirement for manufacturing systems to support a strategy in a market environment.

3.4 Complexity applied to "Operational Effectiveness"

Much of the complexity science literature has been applied to the failure of conventional order in structures designed to carry our processes. Other work has demonstrated how the properties elaborated upon earlier can be used in the design or processes.

"One system scientist said that a system is a set of processes that are made visible in temporary structures ...while we have lusted for order in organisations, we have failed to understand where to find it" (Wheatley, 1999)

From the perspective of enabling “operational effectiveness”, research into complex systems can be divided into three areas:

1. Dynamical systems generating complex and chaotic behaviour;
2. Experiments with populations of agents *i.e.* producing and optimising complex behaviour through agent based models;
3. Measurements based approaches.

A major survey of the tools of complexity science and their application (McCarthy *et al*, 2000) established a link between classical definitions of complex systems and manufacturing organizations. They identified ten families of tools, from a knowledge continuum of the abstract to the applied, dealing with manufacturing issues, from the operational to the strategic. Interestingly, they found a broad, intuitive correlation between the “abstract-strategic” and the “applied-operational”.

The view also exists that research in complexity science has failed to deliver the sort of major impact on industrial organisation that may be expected from such a radical new model for systems (Jones, 2002). This is true of the use of complexity science tools within the existing paradigm that are mostly toward the “applied-operational” area of this product space. Also, (with some notable exceptions) very little literature exists looking at the explanation and further development of the lean and agile paradigms. The tools of complexity have instead been used to optimise difficult problems with the current paradigm of thought, rather than inform us of what fundamentally makes new paradigms new or better than our current ones. The examples to this include Jenner’s study of leanness as a self-organising system that embraces the edge of chaos (Jenner, 1998) and the research into the adoption of lean/agile production tools as an evolutionary process using cladistics (Tsinopoulos and McCarthy, 2000).

In addition, there is evidence that at the level of the metaphor and mental model, that complexity concepts are becoming more widespread in strategic thinking and the quest for value at the very highest levels of strategy making (Hamel, 1998; Pascale, 2001; DiVanna, 2003). There is also

some work on the direct application of Boolean networks (fitness landscapes and self organised criticality) to manufacturing strategy (Tan and McCarthy, 2000) and specific topics such as phase transitions in NK networks used to represent plant loading (Kauffman, 2000).

A good illustration of the use of fitness landscapes and NK networks using the parameters of decision making in management is provided by Rivkin and Siggelkow (2002). Here it was possible to demonstrate how the parameters of local alignment to system versus local goals/incentives and senior management review/autonomy can create sticking points for decision makers (agents) on slopes of optimality in fitness landscapes. Hence, it is possible to discuss issues such as the amount of information referred back to the most senior management and the trade-off between local efficiency versus total system (process) optimality, albeit using the bottom-up vocabulary and values of agents. This can be contrasted with cybernetic systems, where the concepts of requisite variety in communications between local and senior management and recursion (*i.e.* where the viable system is to be found within the conventional hierarchy) offer a different insight into the workings of organisations.

As summarised by McCarthy *et al* (2000), and criticised by Jones (2002), examples of the application of this research to solve operational problems industry include:

1. Deterministic chaos has been used to identify better solutions to hard optimisation problems, refine control problems, and gain insight into how chaos may arise in the algorithms of Master Production Scheduling control software (Wilding 1998a; Wilding 1998b)
2. A variety of agent based architectures have been proposed for factory control (Ottaway and Burns, 2000; Baker, 1998) Furthermore, agent-based systems have been used successfully in a number of factory applications, including automotive paint shops and steel fabrication. They have also been widely used in trading models for commodities such as natural gas (Moody & Morley, 1999; Wakefield, 2001).
3. Measures inform the observer of the complex system which entities (or agents) are the most complex and what their impact is on the complex behaviour of the complex system.

1 and 2 use tools to produce complex behaviour that may be recognised in everyday terms, including the existing performance measures used in the business *i.e.* they use the de-abstraction of induction into the real world. It does not, however, provide any insight into the complexity of the system or its entities, only that the system is behaving in a representative and complex fashion. This will not aid fundamental understanding of the system, though this shortcoming is not at issue where the technique is being used to schedule or optimise a particular real world measure.

3.5 Measurement in complex systems

Brunk (2000) takes a restricted view of complexity (compared to Section 3.1), namely that:

"Complexity is a measure of the sensitivity of particles, people, organizations or nations to each other's behaviour. It is the number of potential connections among members of a system that are capable of transmitting disturbances"

His point does however emphasise the importance of connection between the agents in a complex system, and the need for a measurement to understand what is being observed or about which theories and models are developed (recalling figure 3.1).

Returning to the physical science origins of complex systems, when treating complex or chaotic systems as deterministic systems, there is a pair of related measures in common use (Ott, 1993):

- Lyapunov Exponents give a means of characterising the stretching and contracting characteristics of attractors. The set resulting are orthonormal values for the evolving vectors of trajectories;
- Metric entropy (also known as Kolmogorov-Sinai (KS) entropy) is the rate of creation of information as a chaotic orbit evolves, especially the divergence of flows using the sensitivity to initial conditions.

The maximum metric entropy of a system is actually the same as the sum of the values of positive Lyapunov Exponents. Ruelle (1991) reports that Pesin has shown this for Hamiltonian systems and Ruelle for classes of dissipative systems. Metric entropy is of greater interest than Lyapunov exponents, and is related through K-S entropy to a measure that will be used at length in the model proposed by this thesis. This is developed in Chapter 4.

Existing literature in performance measurement drawn from the study of complexity is not widespread. An interesting view taken is that there is evidence of “physical science uncertainty principles” in conventional performance measurement, but that the theories are not being explicitly being used to inform better measures (Palmer and Parker, 2001). For example, Activity Based Costing and the Balanced Scorecard do work but at an aggregated level, an example of self-organization around a “critical few” measures based on corporate objectives that act as strange attractors to system behaviour.

Attempts at measurement therefore need to express complexity in some or all of the values relevant to complex systems:

- Connection between entities in a class and between hierarchical levels in a system (connectedness) with its impact on system behaviour;
- Taking flow as the principle measure of system behaviour, sources of bottlenecks (obstructions to flow) may be read as disorder amplification or initiation.

Examples of measures of complexity are as follows.

The Level Rule

The Level Rule uses algorithmic complexity within hierarchy. Algorithmic complexity is the shortest description of a structure in a given set of terms. This has no probabilistic content, and has been developed for describing structural complexity in discrete systems with predetermined natures (Yagil, 1999). This measure of complexity has been applied to a super-set of proteins, described by a set of amino acids, themselves described by subset of different atoms. It allows multi-level relative descriptions of complexity across different hierarchical levels (*e.g.* proteins in

terms of amino acid complexity or atomic complexity, as a sum of amino acid complexities). This demonstrates that complexity and hierarchical structure are tightly interrelated structures.

Q-analysis

Q-analysis is the study of connectedness through relational mapping between like entities in one set, in terms of shared entities from another, adjacent hierarchical level (set), or the same set. It is another measure of structural complexity, creating a backcloth on which traffic (complex behaviour recognised in other real world performance measures) may be observed and understood. A mapping relation between the two sets determines the sharing. The relation is described by an incidence matrix, Λ , whereby a non-zero value (usually one) denotes the existence of a relationship. The absence of a relationship is denoted by a zero value. Each member of the sets has a Q Value, calculated by the leading diagonal of $\Lambda \Lambda^T - U$, where Λ^T is the transpose of the incidence matrix and U is the unitary matrix. The Q-value is the value of the number of other set members to which it is actually connected. Looking at the set members and the members of the other set they share creates a topological geometry, or complex of individual simplices. This is discussed in more detail in section 4.5.

A relative measure of the disconnectedness of each set member can be calculated. It is expressed as a ratio of the Q-level at which it first appears with the Q-level at which it joins a geometrical simplex with other set members (*i.e.* they all possess the Q-level of identical shared relations with the other set). This is called the eccentricity (Atkin, 1974; Atkin, 1981) The use of this is will be explored in detail in the next chapter. Examples of the use of this technique include supply chains (Singh *et al*, 2002), town planning and university administration (Atkin 1974), large organisations such as manufacturers (Atkin, 1978), electrical power grid failure (Gould, 1981) and television programme classification (Gould *et al*, 1984).

Information Complexity

Information complexity (its proportionality Kolmogorov complexity) has been used as a measure of complexity in flow systems in the form of the entropy generated. Examples of studies include factories in supply chains (Calinescu *et al*, 1998; Efstathiou *et al*, 2002), and within factories

(Campomanes, 1997; Frizelle and Woodcock, 1994) *etc.* Based on a definitive number of observable states, it is a probabilistic technique whereby the dynamics of queues in front of queue server entities and observed states of entities give an indication of the relative magnitude and reasons for obstruction to flow of each queue server. This may be viewed as the total operational complexity and a subset called structural complexity, comprising just the dynamic behaviour of the queues. This is useful because the entropy property is additive (Frizelle and Suhov, 2001).

The final two measures are of interest in the study of dynamic processes in complex systems because they allow both structure and dynamic behaviour to be viewed concurrently. This is useful in enacting a manufacturing strategy by imparting a designed or emergent structure to a manufacturing system and process flow, whilst being able to understand performance in terms of complex systems. Q-analysis and Entropic measures will therefore form the basis of subsequent discussion in the next section. Level rules will not be considered further.

3.6 Conclusions

From this chapter it is possible to conclude that the study of complex systems has many academic roots and is a broad field of study. The properties that make complex systems interesting to study are directly applicable to manufacturing systems. However, as yet, the literature shows that this has been restricted to complex behaviours as dynamical systems, optimisation problems, and even metaphors for organisation change. There has been less abundant but more encouraging work (from the perspective of this thesis) in measurement and description of manufacturing systems and the drivers of "operational effectiveness".

For research questions 1 and 2, it is possible to conclude that whilst complexity science is making some in-roads into ideas of "operational effectiveness" it is very limited and driven by the complexity science community. The ideas behind complex systems are not widely embraced in conventional "operational effectiveness" literature. Holonic manufacturing is one exception, but this is seen as a facet of the new paradigm of agile manufacturing rather than a source of new

insight or explanation of “operational effectiveness”. This also applies to the subject of performance measurement in manufacturing systems, where evidence of only a single use of complexity science to explain the efficacy (or otherwise) of performance measures has been found under the guise of the “uncertainty sciences”.

This chapter has shown that there are some interesting measures of complex system behaviour that it will be shown are readily applicable to manufacturing systems. The next chapter will describe how agents of interest in a (complex) manufacturing system may be defined as part of an overall structure, and then complex system measures taken of their behaviour and structure.

The null hypothesis framed for research questions 1 and 2 can therefore be rejected by the findings of chapters 2 and 3.

CHAPTER 4 - MODEL DEVELOPMENT

4.1 Introduction to a model for studying manufacturing processes

This chapter will present a model for the study of manufacturing systems in a way that relates both to complexity science, discrete event simulation and the state of the art in manufacturing “operational effectiveness”. In doing so the chapter will identify the agents of interest, the patterns of complex behaviour and structure, and consolidate these into a single model. Thus the null hypothesis as framed in research questions 3, 4 and 5 will be rejected.

The model comprises a framework for description of the manufacturing system and the use of a pair of measures from complexity science. It can be viewed as shown in figure 4.1.:

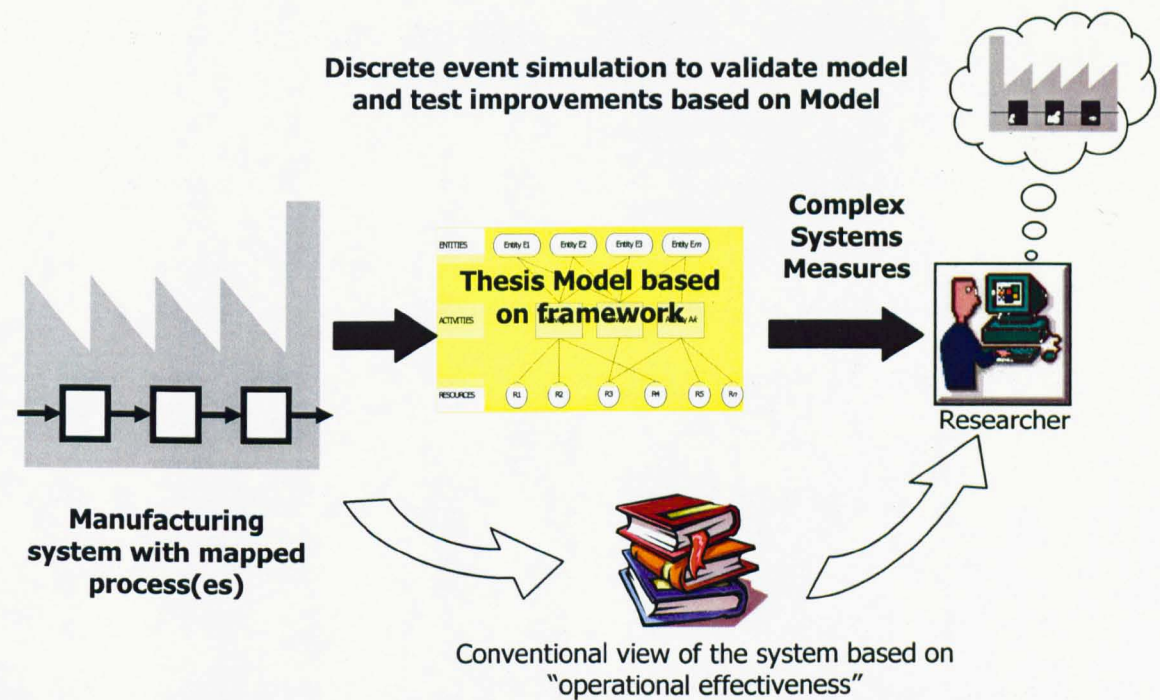


Figure 4.1 – The complexity-influenced model (component parts shown in bold)

In this chapter a complexity-influenced model for the manufacturing system is introduced and described (thus making a proposal to for research question 5). This model incorporates two of the novel contributions from the work of this thesis:

- A framework structure for formally representing a manufacturing process (comprising entities) as a complex system (comprising agents) is described in the remainder of this section and in section 4.2. This builds on elements of the vocabulary of “operational effectiveness” that will be recognisable to a practitioner familiar with this literature. The practitioner requirements of such a framework are further defined in section 4.3. This addresses research question 3, whereby a framework has been developed to identify the agents of interest in a manufacturing system;
- A pair of measures is defined from the complexity literature which provide measures for structure and behaviour in a manufacturing system in complexity terms, but which may be consistent with the “operational effectiveness” worldview. This then proposes to address research question 4, which seeks patterns in complex structure and behaviour. The two measures (identified in section 3.5) are then described in sections 4.4 and 4.5.

The synthesised model is then validated against the essence of the “operational effectiveness” literature highlights in section 4.6. This provides a high-level reality check that the model is exhaustive enough to provide a consistent view and also has adequate scope for additional insights asserted in the thesis title. This supports the complexity-influenced model offered in response to research question 5.

4.1.1 Framework for Entity classification

A manufacturing system can be made up of a huge number and array of people, objects, information and interactions. The following requirements of a system definition tool and language for parts and interactions may be listed:

- There needs to be a common set of terms used for comparison between use cases of the definition in various experiments;
- The set of terms needs to relate to those of complexity science;
- The system definition must allow experimentation and modelling;
- The system must relate to the recognizable real world measures, control parameters and noise factors afforded the managers of manufacturing systems.

Because of its roots in the study of systems, modelling can provide clear guidance on how to categorise the component parts (and their interaction) of manufacturing systems in order to study them. Looking particularly at discrete event simulation, it is important to define:

- The system boundary and environmental conditions;
- Entities representing functions / activities that are being carried out;
- The entities being produced/worked upon by the system;
- The entities required to carry out each activity.

Entities as defined by these models are therefore the component parts of these models. The interactions between them are implicit in the definition of the entities. This is normally done by defined routings in the entities that are produced or by conditional rules in activity entities.

This form of description method is more useful than a functional decomposition technique because the classification of what is being mapped is implicit in the definition of the parts and system. In functional decomposition (such as IDEF₀), there is no assurance that the classification system adopted for the system and its parts is actually being used. It is, however, a very useful way to identify what is going on in a system and what the actual parts are. For that reason, these techniques remain extremely useful, and the IDEF₀ system block is shown in figure 4.2.:

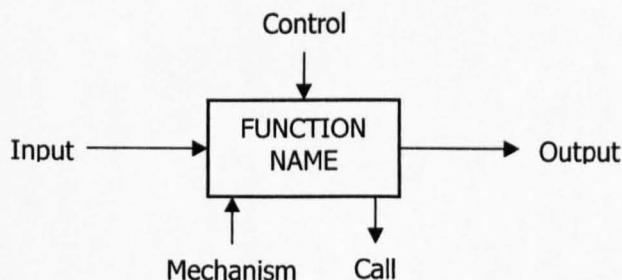


Figure 4.2 The IDEF₀ Function Block (reproduced from Figure 3 of Federal Standard "IDEF₀: Integrated Definition for Function Modelling" (source: FIPS183, 1993)).

The system of classes and inheritance in object-oriented and (more recently) holonic-manufacturing literature may be used actively to provide a classification system of the real world. The view of the manufacturing system is a particular hierarchical set of component parts (holons), and is not too far removed from defining the same parts as agents. This sort of system definition therefore lends itself readily to agent-based simulation.

4.1.2 A framework proposal for manufacturing systems

To apply the concepts of classification and hierarchy to manufacturing systems, the following three types of entity have been selected:

- Material or information that are converted or consumed in the process of realising a product. The assertion made here is that this can be either material or information in nature and that processes can interchange these. These are going to be called Entities. In comparison with the IDEF₀ function block, these are Inputs and Outputs;
- Process steps conducted to realise the Entity defined above are going to be called Activities. In IDEF₀ terms, this is the Function Name. These are the operational practices and work structures rather than the actual physical artefacts used. This distinction can be extremely difficult to draw, especially where there is a 1:1 mapping relationship between the activity and the artefact, *i.e.* the activity being executed to carry out a particular operation on a product and the resource used appear to be the same entity in modelling terms. It is important to separate these, as there is a source of richness in mappings that are not 1:1;
- Things used to carry out the Activity are going to be called Resources, or Mechanisms in IDEF₀ terms. Within this, the variety and need for further categorisation could potentially be enormous. Drawing on the literature of modelling and Optimised Production Technology (OPT) together, there is a precedent to assist the choice of what should be included in this set. Both of these areas of literature assume that resources should only be included if they will interrupt flow if they are in contention or become unavailable for carrying out the activities of the model.

There are three sets of “things” in this classification for manufacturing systems, borrowing extensively from discrete event modelling. These usually have two distinct part sets, but have scope for a whole host of activity/resource parts, depending on what is required to make the product (defined by the modeller).

It is important to understand the sense in which this can be seen as an agent based system. In this model, only the resources are assumed to be agents (other models also have entities as agents). In the model the agents are governed by the following rules that the agents will carry out an activity on an entity given that:

- There is a suitable entity to carry an activity out on;
- The agent is not carrying out an activity on a different entity;
- The agent is not switching between entities;
- The agent is not incapacitated from carrying out an activity on an entity;
- The agent has the requisite attributes to carry out then activity on the entity;
- Where there are two or more entities present, there are unambiguous rules for selecting one;
- The internal states of the agents (resources) are simply the activities it carries out. There are four classes – idle, make (busy), changeover (set-up) and breakdown (downtime).

The significant point is that, as will be shown, the measures that are developed link directly to the internal states of the agent. Thus they apply at the individual agent level, not at system level.

The measures’ nature is not reductionist.

It has also been shown that a major part of the richness of a complex system will come from the interconnectedness of parts and their environment. Using these three sets, the following logical relations (R_{MN}) exist, based on the criterion for a relation between two sets M and N being that N is used in M. There are various logical ways to establish each relation. All likely relations are considered, and the ones that will be used are selected because they are meaningful in defining, designing and making investment decisions in the system:

- R_{EA} is the relationship between Entities and Activities. This draws on the Value Stream Mapping and Management concepts that a product (Entity) is the sum of the Activities that it undergoes in being converted to a finished item. High degrees of connection between a set of Entities and Activities implies that one or more of the following is true:
 - There is a great deal of Activity sharing between Entities (commonality of product routing), the result of logical AND relationship between Entities for a given Activity;
 - There is scope for process design flexibility (alternatives), a logical OR between Activities for a given Entity;
 - A further AND relationship (sequence dependant or otherwise) for the set of Activities required to produce an Entity.

For the processes under consideration, the first and third relations will be included. The second has been discounted as good practice in processes description should not allow this unless there are fundamental differences in their manufacture *e.g.* machining a metal component complete from a solid billet versus a near net shape process followed by finishing machining;

- R_{AR} is the relationship between Activities and the Resources that are used to carry them out. This set of Resources is limited to those of particular interest from a modelling point of view, as described above. The possible relations are as follows:
 - The AND relationship between an Activity and the Resources required (in conjunction with one another);
 - The OR relationship between an Activity and the Resources required (alternative routings, redundancy in the resources capable of carrying this Activity out);
 - The AND relationship between a Resource and the Activities that it can carry out (concurrently, by implication). An example of this would be a batch oven that can carry out long and short processing cycles at a given temperature just by controlling when particular parts are loaded and unloaded. This oven could be of interest because it may be a capacity constrained resource.

The OR relationship will be the only one considered here because only one limiting Resource per Activity is going to be considered when defining the sets of Resources and

Activities. This does give a partial description of the system, which is potentially limiting. The validity of this assumption and simplification will be tested on a per-experiment basis in subsequent chapters. Similarly, AND relation of Activities carried out by Resources such as our theoretical oven requires closer examination. In modelling terms, no information is lost by relying on just the OR relation, as long as the importance of the temperature setting and absolute capacity of this Resource is also defined;

- R_{ER} is the relationship between the Entities and the Resources used to carry out the Activities used to make each Entity. If the definition of Entities, Activities and Resources is correct, then there should be no need for this relation to exist explicitly. Returning to our oven example from earlier, if a long item (call it Entity A) is too long for the oven but requires a particular time and temperature (the length attribute not being defined), then the same Activity ("Bake for X minutes at Y°C") will erroneously specify the same Resource as for Entity B (which is just the right length for the oven). This does not require an entity-specific Resource relationship, however. Instead, the Activity needs to capture the attributes of Entities A and B accurately (including lengths), predicating that different types of ovens will be required. This will therefore require two Activities (the second could be "Bake a long thing for X minutes at Y°C"). This accurate capture of the correct attributes of Entities (with the implications for Activities and Resources) has been a focus of both discrete event modelling and Holonic manufacturing research. Based on this argument, this relationship will not be considered further. However, it is important to note that R_{ER} is the actual mapping relation under study when the server queue length and state observations are made to derive entropy measures. Entities in queues at Resources (carrying out Activities and sometimes not carrying them out, as in the case of a DOWN state) are an example of the R_{ER} relation being measured dynamically. This is covered in detail in section 4.5.

The result of these Relationships is the Entity-Activity-Resource (EAR) framework, shown in terms of set membership of cover sets in figure 4.3.

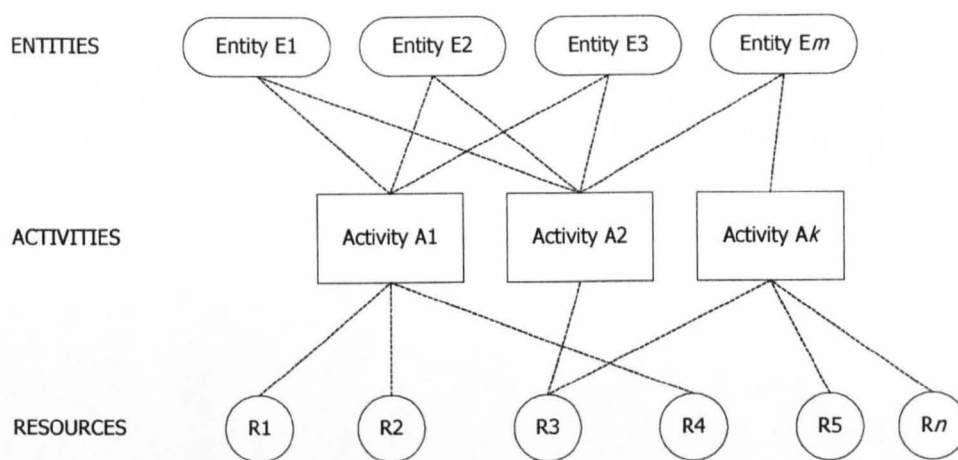


Figure 4.3 – Cover sets for the Entity Activity Resource framework

4.2 Model construction using complexity as the evolution of General Systems

Theory

4.2.1 The contribution of Cybernetics to the model

Cybernetics (Beer, 1985) uses variety, expressed as information to measure the fitness of flow in the processes of an organisation. The cybernetic view of organisational viability is dependant on the existence of a series of functions for the process of management, connected by communication channels of bandwidth equal to the requisite variety of the environment, noise and control functions.

The operation of each function, both in terms of its own fitness and location relative to other functions determines the effectiveness of the total system. Again the measure is that of the ability of each function to cope with, create and attenuate the different types of variety abundant in the system in the execution of its role in the system.

A criticism of cybernetics is that it assumes a hierarchy of command and control, and is a relic of centralised, functional bureaucracy, with an elite few thinking and hordes of others doing their bidding. If applied literally, then such an organisational form may result. Rather, it is a set of activities which cyberneticists deem necessary to be found in different parts of the viable

organisation whole, connected by the principles of variety management. How these are codified in terms of organisation structure is limited only by the imagination of the designer. Nowhere are levels of seniority assigned to the different functions – it is however obvious that co-ordinating the activities of two or more operational units needs to be undertaken by someone who has adequate visibility of the units in question. Hence the criticism described is more a measure of the lack of creativity of those applying the principals than a set of situation-specific prescriptions from cybernetics.

Countering this criticism yet further, an assumption in this model is that the principles of cybernetics are as applicable to all forms of organisation in processes, and not just the type of bureaucratic, functionally organised business that predates Business Process Re-engineering, albeit still very commonly found in manufacturing. The contribution of cybernetics that will be developed further in this model is the use of information as a measure of variety, and the forms of variety as a measure of complexity. Furthermore, the inability of a resource carrying out a function to successfully handle a quantity or type of variety, (or attenuate variety attributable to environmental noise) demonstrates that such a resource obstructs viability because it is an obstacle to flow (organisational fitness). In IDEF₀ terms, variety may be the transformation of Input to Outputs, or the use of Control and sharing of Call information. The use of the variety concept in the relation to the Entity Activity Resource framework will be expanded upon in later sections.

4.2.2 Demonstrating a fit between the Entity Activity Resource framework and Agents in a Complex Adaptive System

Earlier sections have shown that the principals of the Entity Activity Resource (EAR) framework use the nomenclature set of IDEF₀ function block, but also use hierarchy (as is found in class definitions in object orientation). These are both well used in simulation modelling, which derives its definitions from within systems theory (Pidd, 1982).

It has also been shown that object orientation is very similar to the definition of Agents as would be found in a Complex Adaptive System (CAS).

It is possible to conclude that the EAR framework as applied to processes can also create consistent definitions for the Agents of a CAS. Complexity exhibited by the system under study that is represented in terms of the EAR framework can therefore be related to the behaviour of the members of the sets in the same way that Agents may be used.

The fundamental difference between these approaches is that the EAR is a measurement-based framework, and the EAR set members are *measured* whereas Agents in a CAS are used through simulation to *produce* complex behaviour *in silico*. To test that the measurements relate to the complex behaviour of the EAR set members, a simulation stage is therefore required to support the connection between measures taken on the EAR set members and how this behaviour is brought about. This simulation needs to verify the following before it can be used as a tool to investigate possible interventions made to the EAR framework:

- Validate that the subset of all system parts summarised by the EAR framework can produce the sort of system behaviour that has been observed;
- Validate that the interactions/rules of the selected system parts can produce the sort of system behaviour that has been observed;
- Demonstrate the link between complex systems described by the EAR framework of Agents and normal performance measures of system behaviour employed in the business.

4.3 Requirements of an integrated experimental model using flow and the Entity Activity Resource framework

To summarise the requirements of a model based on an integrated, joint measurement approach (to be based on the EAR framework), the following must be possible:

- It must be possible to compare the flow and structural measures. To do this the model must use a self-consistent EAR framework for both flow and structural measures;

- The flow measure must relate to a measure of a significant determinant of system performance *e.g.* as variety does for cybernetics. This implies that an understanding of the incumbent system measures (and the reporting objectives they are supposed to fulfil for the process owner/manager) is required;
- The structure measure must relate to interconnection (*i.e.* scope for richness) and potentially be a significant determinant of complexity of the system under observation;
- It must be possible to validate behaviour observed in terms of the EAR hierarchy adopted, through the objectives of simulation validation, outlined above (section 3.3). This requires that the same EAR structure be used in the validation model. The model (constructed using the interactions assumed in the EAR structure) should also produce similar flow behaviour to that which has been observed in the real system;
- It must be possible to relate the measures to the business performance drivers that can be influenced in terms of interventions to the EAR framework. These are the sort of changes that process owners/managers could make through product and process design, resource allocation *etc.* This creates something of a paradox. Carrying out such a measurement based study of a system may inform the process owner/manager of what the real or most effective performance drivers are, yet the study requires that the known drivers are included in the EAR structure. There is a further complication – ideally the model will not exclude any unknown performance drivers. This is in fact an expression of the well-documented problem of knowing what to include in the model (hence EAR structure). The only solution is diligence in capturing system operation, model validation and iteration as required;
- Measures must allow direct comparison of set members in each set within the context of the whole system. For example, the relative connectedness or obstruction to flow of each set member (where the set in question in the EAR structure is subject to the focus of the study);
- Measures must allow root causes to be better understood *i.e.* relate back to the mechanics of the system (structural or flow-based) rather than just summarise the observations being made.

4.4 Measure I – Information theory, Entropy and Flow

4.4.1 Introduction – Queues and Servers

The IDEF₀ process model can be expressed in the terms of simulation modelling and the EAR hierarchy as shown in figure 4.4.

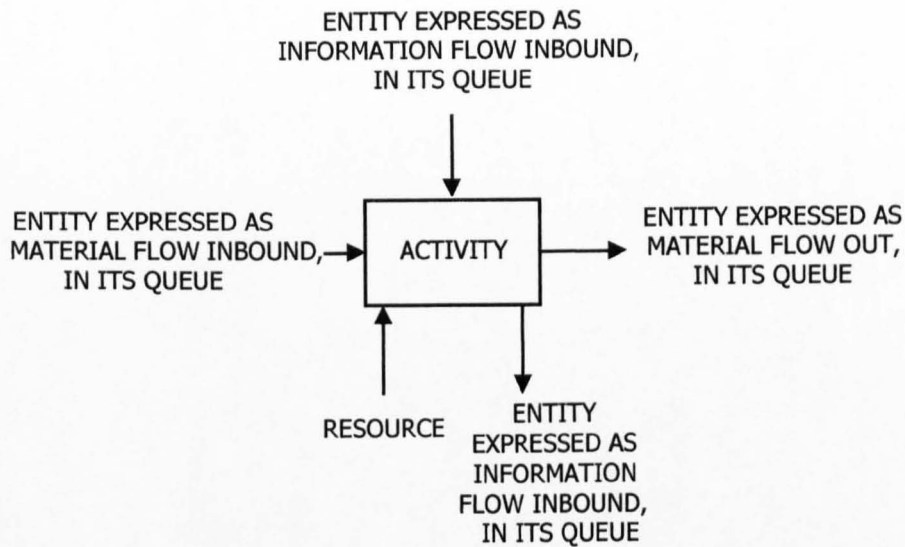


Figure 4.4 – Entity Activity Resource applied, using an IDEF₀ process block

The constituent parts of this figure are the server (an Activity carried out by a critical Resource) and its upstream queue (material or information used as the most relevant way to describe an Entity) at a particular point in a process. This feeds the downstream queue(s) which are served by further connected servers (Activities). The upstream queue for every server is formed when arrival rate (λ) exceeds the service rate (μ) of the activity. The greater the uncertainty involved in observing the queue and server, the greater the information content of it will be.

Subject to the classification of what is being observed, a number and frequency (probability mass) of each of the different states will be seen. When observing queue/servers, the queue length and state of the server are simultaneously observed. Drawing from communications theory, the expectation of the information seen is the Shannon Entropy of a set of n observations of a discrete random variable X of probability mass function $p_i(x)$ at time i . This Entropy is given by:

$$H(x) = -\sum_{i=1}^n [p_i(x) \log_2 p_i(x)] \quad (4.1)$$

Where $\log_2 p_i(x)$ = the information content in binary bits of $p(x)$, and

And $H(x)$ = is the expectation of the information content of $p(x)$.

$H(x)$ is independent of the actual value of X , and is concerned with the probability distribution of X (the range of queue and server states).

The Shannon entropy is equivalent to within a constant of the Kolmogorov Sinai (KS) Complexity value of computer science, for the minimum descriptive complexity of a programme to print out a string of numbers (or in this case states). The condition for this equivalence is that the sequence is drawn at random from a distribution of entropy H .

To demonstrate that this is a measure of obstruction to flow, Frizelle and Suhov (2001) produced the following measure for queue servers. For these systems with a 1:1 correspondence of its states to the natural numbers, the geometric distribution maximises entropy (KS entropy is an upper bound) where the probability is that of first success of observing a state.

Considering Bernoulli trials of the random variable of this probability, the probability of observing a state at the i^{th} event is given by $p^{i-1}(1-p)$. The mean of the geometric distribution is defined as

$$E(x) = \sum_{i=1}^{\infty} i \cdot p^{i-1} = 1/(1-p) \quad (4.2)$$

Where $E(x)$ = the mean (expectation) of the probability mass function. The entropy of a geometric distribution can be shown to be

$$H(S) = -1 \cdot [p \cdot \log_2 p + (1-p) \cdot \log_2 (1-p)] / (1-p) \quad (4.3)$$

This can be shown to be the entropy of a type of queue server called a M/M/1 whereby:

- M denotes Markov arrival rate (λ) based on a Poisson distribution;
- M denotes a Markov queue server rate based on a negative exponential distribution (μ);
- 1 denotes a single server per queue.

In this application of the geometric distribution, the probability is that of finding a particular queue, given the traffic intensity defined as p being equal to λ/μ . The probability of finding no queue is accordingly given by $(1-p)$.

The properties of the entropy of this M/M/1 queue server are that the gradient is monotonic/isotonic *i.e.* always positive, and that the average queue length tends to infinity as the traffic intensity p tends to the limit of 1 *i.e.* full capacity of the queue server. This is because the expectation is that of the geometric distribution *i.e.* $1/(1-p)$. The result is that waiting time tends to infinity with average queue length and the predictability of the wait time in the queue reduces (*i.e.* the queue becomes more dynamic in nature).

The Entropy is therefore a very interesting measure on a queue server because it relates to the KS complexity measure, and it reflects the operational performance of that queue server.

4.4.2 A Measure for the Observations of production systems

There are a number of different aspects of a measure based on entropy, for the requirements of section number 3.4 to be fully met. The queue/server observation contains three component parts:

- Tolerated/Non Tolerated state, T . Any queue is evidence of a non-tolerated state and so the measure is practically concerned with non-tolerated states only:
- Queue length, q , excluding what is being processed by the server
- Nature of server state, s . Four have been universally adopted. Where it is not possible to ascertain the state, an unknown state is then identical to the entropy of queue length variation only as no additional information is created:
 - Make – carrying out productive work;

- Idle – inactive without a queue;
- Breakdown – inactive with a queue due to shortage of Resources, Entities, equipment reliability;
- Setup – changing over from one Make state to another.

The joint entropy $H(T,q,s)$ is given by a chain rule expansion for Entropy (Cover and Thomas, 1991) is thus:

$$H(T,q,s) = H(T) + H(q|T) + H(s|q,T) \quad (4.4)$$

Where $H(T)$ = Entropy of tolerated states;

$H(q|T)$ = conditional entropy of queue length q for a given tolerated state T ;

And $H(s|q,T)$ = conditional entropy of states s for a joint entropy of queue length q and tolerated state T .

However, given that only non-tolerated states are practically observed, this can be simplified to a joint entropy of q and s :

$$H(q,s) = H(q) + H(s|q) \quad (4.5a)$$

This is equal to the entropy of the queue $H(q)$, plus the conditional entropy of the server states given the queue $H(s|q)$. The queue entropy component $H(q)$ is the most valid measure of obstruction to flow based on the discussion in the previous section. The joint entropy is also equivalent to

$$H(s,q) = H(s) + H(q|s) \quad (4.5b)$$

This is equal to the server entropy plus the conditional entropy of the queue states given the server. Expressed as the probability based on the frequency of observing an event made up of state and queue length, the conditional entropy term $H(q|s)$ may be expressed thus:

$$\begin{aligned}
H(q|s) &= - \sum_{all\ q} \sum_{all\ s} [p(s,q) \cdot \log_2(q|s)] \\
&= - \sum_{all\ q} \sum_{all\ s} [p(q) \cdot p(q|s) \cdot \log_2(q|s)] \\
&= - \sum_{all\ q} p(q) \sum_{all\ s} [p(q|s) \cdot \log_2(q|s)]
\end{aligned} \tag{4.6}$$

where the later summation is the entropy of conditional probability, not a conditional entropy. To calculate the total values using the observations, the following expansion is required:

$$H(q,s) = - \sum_{all\ q} \sum_{all\ s} [p(q,s) \cdot \log_2 p(q,s)] \tag{4.7}$$

Just as equation (4.1) is important for the entropy calculation of each queue length / server state probability, so equation (4.7) is critical to applying it as a measure in the observation of real systems.

Hence in taking observations, a set of joint probabilities of each coincidental state and queue length may be taken. However, the additive property of joint entropies allows easy separate calculation of the queue only and server state contributions to the obstruction to flow.

With this framework available for each Resource carrying out a particular Activity, there is a requirement to be able to construct networks of interconnected queue/servers. This is to express the Activity-Activity precedence/connection relation studied by Singh *et al*/(2002), referred to in this research as the type R_{AA} .

To synthesise individual M/M/1 queue-servers into production systems, Frizelle and Suhov (2001) were able to use the properties of Jackson networks of M/M/1 queues, whereby the entropy measurement for the entire network is the sum of the individual queues. This is possible because the queues behave as if they are independent at any one time, allowing separate and instantaneous observations to be made to derive a set of frequencies (hence probabilities) of queue lengths and server states. It is therefore possible to construct observable networks of activities (carried out by resources) to produce entities for customers in the systems under study.

4.4.3 Contribution to the complexity-influenced model

The entropy measure gives the observer insight into the relative contribution to the obstruction to system flow of Entities at each Resource queue/server carrying out an Activity in their value stream. This is shown by looking at the queue component of the entropy measurement for each queue/server. It has been shown that the cause of the obstruction at that queue/server is the service rate falling below the arrival rate. The cause of this is recorded in the server state definition at observation, of which the convention for four states has been retained. Returning to the EAR framework, whilst a Resource is the physical thing being observed, it is actually the Activity that is (or is not) being carried out that is of interest. This is how the user of the model measures whether the Entity is being produced or not (which is the purpose of the entire system).

The implication of this for the measurement of flow is that the Activity is the queue/server of the flow measurement. The flow behaviour is allocated a server state at each observation, and an analysis by server state of the contribution of each server state to flow obstruction can be performed. From the EAR hierarchy, the Relationship between Activity and Resource, (R_{AR}) or Entity and Activity (R_{EA}) may be substantial determinants of flow behaviour. Given this possibility, it is critical to have a measure of the structure of the Relations between the member of these sets.

4.4.4 Worked example of the use of Measure I

For a single queue server, the following queue lengths and server states were observed (see figure 4.5). Considering the entropy with queues, it was possible to calculate the entropy with states as shown below. Summing the Entropy results shows that the contribution to the total entropy measure using equation (4.7) can be obtained by summing queue lengths over each state.

$$\text{state B (breakdown)} = 0.1590404 + 0.1590404 + 0.1296919 = 0.4477727$$

whereas the total entropy measure from

state $M = 0.0697374 + 0.1060269 = 0.1747643$.

The obstacle to flow of B (breakdown) far outweighs that of the M (make). Hence it is possible to conclude that equipment unreliability rather than a genuine shortage of production capacity with cause a flow obstruction at this queue server.

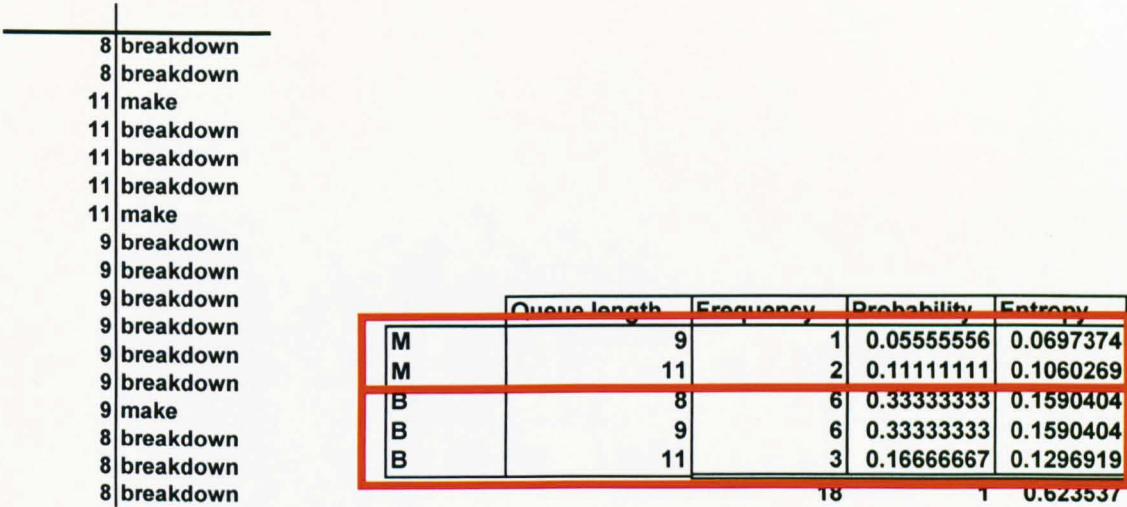


Figure 4.5 – Entropy worked example

A full worked example of this calculation process for one of the case studies is available for the case study in Chapter 7 in Appendix section B.3.

4.5 Measure II – Q-Analysis and the EAR Framework

Q-Analysis has been used in a wide variety of applications to describe the connection of two sets of things. This connection is due to a relationship, R between members of each set. The result is a geometrical complex made up of simplices of the individual relationships connecting individual members of each set. The relationship is recorded in matrix form.

The same set membership can be used twice as both original and incident set (*e.g.* a league table of tennis players, in which the Relation of interest is “who has beaten whom” is recorded).

Furthermore, the relationship can either be binary in nature (*i.e.* the Relationship is True or False) or it can hold a numerical value (a weighted relation). This latter, less common case is illustrated (Atkin, 1974) by numbers of observed cars on roads connecting different places. In this case, the different locations are the two sets (from and to), the road going from place to place acts as the Relation (*i.e.* connection), and the number of different types of observed vehicles the weighting of the relation. As a further aid to visualisation, Atkin draws the analogy to an area of cityscape with buildings of different heights (each building is an instance in the weighted matrix). This allows for a slicing analysis, where the matrix of the relation is turned into a binary matrix of 1’s and 0’s, by slicing the matrix at different “heights” (*i.e.* a slicing parameter). This is illustrated in Figure 4.6 below.

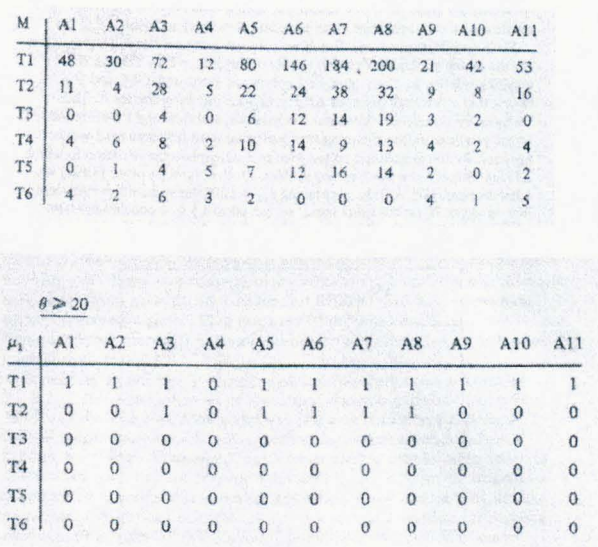


Figure 4.6 – Example of a slicing parameter ($\theta \geq 20$) in incidence matrices (Atkin, 1974, p37-8)

This is of interest because it is possible to see how the connection geometry changes for different “heights” or strengths of relationship. This may be particularly useful when catastrophic conditions are observed in a system, and small changes produce much larger outcomes. By analogy with Q-Analysis, small changes to the “height” of the slicing parameter can produce very different connection geometry and resulting system description. Hence in instances where

connectivity determines system behaviour, the slicing method should reveal if the system is prone to catastrophes from small parameter changes.

The other measure derived from the geometry is a ratio of the absolute disconnectedness of a set member from its peers, called Eccentricity. As with all Q-Analysis this connectedness is derived from the number and choice of members of the incident set which are shared with its peers. This is calculated as:

$$\text{Eccentricity (Ecc)} = (\text{top-}q - \text{bottom-}q) / (\text{bottom-}q + 1) \quad (4.8)$$

Where

top- q = the highest dimension (Q-value) at which an element is connected in the structure
and

bottom- q = the highest dimension (Q-value) at which it first becomes part of the geometry *i.e.* becomes connected to other set members in an equivalence set.

The eccentricity value provides insight into not only how much connection a set member has, but also how these connections affect the geometry and creation of simplices. In the context of the EAR framework, it gives a measure of the degree of integration of the set member in question into the structure. A full worked example of the algorithm for the Q-analysis and eccentricity calculation are given in appendix sections B.4.1 and B.4.2 respectively for the case study in chapter 7.

In the construction of the EAR hierarchy two relationships are obvious between the three sets of things – relationship R_{EA} between Entities and Activities, and R_{AR} between Activities and Resources. The assertion being made is that the interventions taken to improve operational effectiveness (in support of a strategy) may be described as altering the membership of, or Relational geometry between, the sets. To test the assertion, the aspects of the process view of manufacturing that were discussed in the literature (Sections 2.3.2 and 2.3.3) are going now to be reviewed in the context of set membership, connected by relational geometry.

4.6 Validation of the effectiveness of the model

The following summaries of operational effectiveness are of interest. It is therefore important that the two measures placed on the Entity Activity Resource framework (see sections 4.4 and 4.5) can provide insight in the context of the following conventional frameworks for “operational effectiveness”:

- The focus on seven types of waste, identified by Toyota and adopted by the quality movement, which has most recently been augmented with an eighth by Liker (2004);
- Spear and Bowen’s (1999) four rules of the DNA of the Toyota Production System (TPS);
- Schonberger’s (1996) Quality, Speed, Flexibility and Value (QSFV) framework for World Class Manufacturing;
- The link with strategy provided by Brown’s (2000) Enlightened Manufacturing – achieving Quality, Flexibility and Innovation in the market by a combination of Process Technology, Human Resources, and Inventory management;
- The HITOP (High Integration of Technology, Organisation and People) model for Agility proposed by Kidd (1994).

4.6.1 The Seven Wastes

If relevant to gaining an insight into a process, the each of the seven wastes can be neatly attributed to an observed state in an Entropy study. Most interestingly, the eighth waste of not using employees’ latent potential or creativity may be the most difficult to qualify using the joint measurements. By mapping and observing the system, it will be possible to develop a subjective “feel” for the support and nurturing of innovation in the organisation.

4.6.2 The DNA of the Toyota Production System

The four rules of the DNA of the Toyota Production System, and their coverage by the joint measures are:

- Standardisation and work standards. The clarity and crispness of Activity definitions and how readily this may be mapped onto skill sets possessed by Human Resources will be a qualitative measure;
- Direct connections between supplier and customer. Entropy measurement will demonstrate how efficient flow is through the value stream of each entity's set of Activities;
- Unambiguous linkages based on Yes/No connections between supplier and customer. The mapping of Activities in series to provide a built-up whole on a per-entity (product) basis should reveal whether linkages between Activities are based on simple or complicated relationships, determining flow behaviour. Other than the efficiency of the flow, this will be a further qualitative measure;
- All process changes are made from a scientific/experimental basis, at the lowest level possible in the organisation. Qualitative evidence should suggest how change is made within processes when observing operational problems. Interestingly, this is a potential use for a cybernetic approach, where the appropriateness of recursion of viable systems could be critiqued. This will not be possible using just the joint measures.

4.6.3 Schonberger's Quality, Speed, Flexibility and Value (QSFV)

Taking Quality, Speed, Flexibility and Value in turn, we see that:

- Quality may be related to performance pertaining to the seven wastes (see section 4.6.1);
- Speed may be measured through the flow performance of the system, the relative entropy of the set of items under study;
- Flexibility has many dimensions, and Upton advises that the correct dimension be focussed on and pursued to support operational strategy. If looking for alternative routing or resource allocation type of flexibility then a measure of the connectedness of the system's resources to its different activities (the R_{AR} Relation) will provide insight. Excess capacity/volume flexibility will be less measurable, but the amount of capacity headspace may be gauged by the flow behaviour of the system under the type of loading

seen during the study period. New product introduction / innovation type flexibility will be discussed in section 4.6.4;

- Value as a proportion of activities for which a customer is prepared to pay versus that for which they are not is described by the existence of value adding Activities (useful and wasteful activity) and non value-adding Activities. The Activity definitions in the EAR hierarchy, plus the observations of waste in the system (see section 4.6.1) will provide an insight into this. These are both relative measures, based on the notion of value as a ratio. The measurements will not provide an absolute measure of how much value is being delivered for the customer.

4.6.4 Enlightened Manufacturing

Quality and Flexibility (see 4.6.3) will be easy to measure and understand using the joint measures. Innovation will be more difficult, but the ability to support innovation through flexible response and ability to manage product complexity (novelty) without creating obstacles to flow can be measured. The Relationship between Products and the process steps undertaken to make them may be investigated through the Entity-Activity Relation, R_{EA} . Enlightened manufacturing states that the key to delivering these is a focus on Process Technology, Human Resources and Inventory Management (the latter especially with supply chain partnerships). The former two are discussed in 4.6.5 (see below). Inventory management performance within the process under study can be readily measured by the queue observations of an entropy study.

4.6.5 High Integration of Technology, Organisation and People (HITOP)

This model for Agility focuses on the integration of Technology and People in Organisations:

- Technology can be understood in the context of which Activities are defined in the process, and how they are realised by Resources. This implies scope for insight from both the set memberships and connections Activities and Resources. The efficacy and efficiency of process technology (and the People using it – see below) can also be studied in the context of system flow performance from the entropy study;

- People can be understood in the context of the number and range of activities they carry out (skills they possess) and how they are connected. Lean manufacturing and business process reengineering predicates the extensive use of the concept of the standard operations. The ease of the Activity mapping exercise will reveal how readily this concept has been adopted by the system under study;
- Organisation can be understood in how human resources are connected through activities (*i.e.* which skills they possess). The reconfigurability (a critical aspect of agility) of the organisational form to respond to turbulent market conditions is difficult to measure.

4.6.6 Summary of validation of the model within “operational effectiveness”

It has been shown that the structure and behaviour measures proposed in this model relate closely to the dimensions and determinants that the current literature associates with “operational effectiveness” in manufacturing systems. There is good coverage of the indicators that have been discussed. There are certain gaps, where a measure will not be possible, and a qualitative view may be formed through carrying out the study. Also, it is unlikely that the measures will identify absolute figures. It is more likely that they will provide relative measurements of system performance. Finally, it must be restated that the incumbent process measurement system must also be considered because it documents:

- The existing assumptions about what are the drivers of system performance;
- Validation that the hierarchy constructed and observations being made are representative of both one another and the actual system being studied.

Based on the insight that these measures might be expected to give an observer of manufacturing systems, the next chapter describes a methodology for their use in manufacturing systems, and how a total framework may be tested.

4.7 Conclusions

The objective of the complexity-influenced model is to provide novel insights from complexity-based measures it embodies about the nature of the “operational effectiveness” of systems that it is used to study. The model can be shown to do exactly this by contribution of a novel framework for the complex system agents as Entities, Activities and Resources (EAR), where the agent (in this case) is the resource, part-answering but not yet testing the response to research question 3.

Using a pair of measures for complexity provides patterns for structure and behaviour, which have been shown to describe the geometry of the relationships between classes of agents and flow behaviour resulting from the structure. Moreover, these measures apply directly at the agent level, being related to the resource states. Therefore they cannot be described as top-down measures. Bowman (1994) was able to conclude an important result from the latter measure used in isolation i.e. when to simplify and when to improve the control of flow. This set of measures at least part answers research question 4.

Finally, this is combined into a model that can be seen fully for the first time in this chapter, and goes towards answering the first part of research question 5. The model comprises:

- A structural framework for agents;
- Measures on the framework;
- Framework and measure validation through comparative Discrete Event modelling and simultaneous “conventional” performance measurement;
- Ready reference back to “operational effectiveness” literature and terminology.

The null hypothesis can thus be rejected in the context of the research questions 3, 4 and 5. The next chapter will operationalise this model in a methodology and taxonomy for case studies to test both model and methodology on real complex manufacturing system processes.

CHAPTER 5 - METHODOLOGY

5.1 Introduction

An experimental methodology is required to investigate the model developed in the previous chapter. This model is based on measurement of existing manufacturing systems, and will focus on a single process per study. A number of studies are planned to test different aspects of the model.

The objectives of the methodology will be to investigate what additional insight we gain about manufacturing best practice models from the use of the two measures (sections 4.4 and 4.5), and thereby:

1. See whether or not the two complexity measures add more knowledge and understanding to a conventional measurement based approach to control and improvement of a manufacturing process;
2. To analyse the emergent phenomenon of a good or bad manufacturing process, based on the established explanations (present in the "operational effectiveness" literature) of what makes organisations lean, agile, enlightened or bad;

5.2 Overview of the Methodology

A set of discrete activities is required for this process and will form the basis of the methodology (see Figure 5.1). There are four principal activities:

- Defining an Entity Activity Resource framework to describe the process;
- Carrying out novel (complex) and conventional measurement in parallel;
- Build a conventional, discrete event model as a platform for validation of the framework and results of the measures;
- Further experimentation and implementation of improvements to further test the understanding and insight gained from the methodology.

Whilst this is not proposed as an improvement methodology per se, it is envisaged that the outcome should offer insights into the nature of operational effectiveness globally and identify specific opportunities local to the process under study.

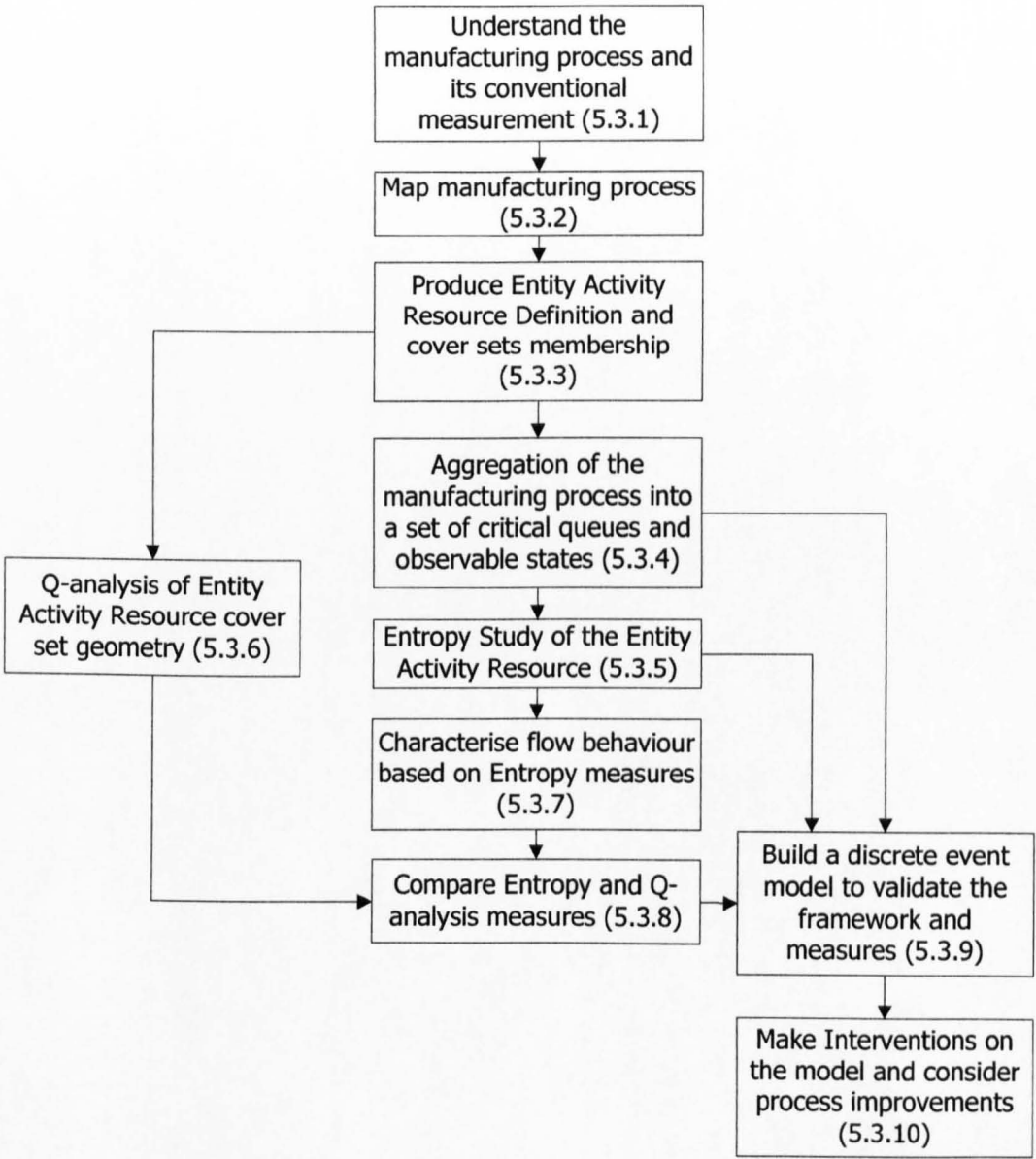


Figure 5.1 – Methodology flow

5.3 Detailed Components of Methodology

The Methodology comprises the following discrete activities described in the rest of this section.

5.3.1 Understand the manufacturing process and its conventional measurement

The objectives of this activity are to understand the context of the process under study:

- The objectives of the process *i.e.* what its output is (Entity) and what role it is filling in strategy deployment;
- What the critical activities, resources, their relationships and decision points are, and what determines the rate of operation of the process. A horizontal audit of an entity through the process will be the preferred way of tracing this. Whilst a capacity constraint resource will not be definitively known at this point, the critical resources and rate determinants will be identified by asking "which other resources (from a particular class) may carry out this activity?". A large potential set of many alternatives within a class identifies that there is some richness, and that this is worth pursuing in later phases of the study;
- Understand in what ways the process stakeholders feel that it is failing to deliver the results required. This can take three forms – failure of the strategy the process is trying to deliver, failure of the total process to deliver the strategy (both are forms of doing the wrong thing right) or failure of parts of the process to deliver. This softer aspect of the methodology provides a context that process stakeholders can then relate to. They can relate the problems they perceive (from their perspective) to concepts such as flow, entropy, and a multidimensional geometrical structure mapping system parts to one another. One of the advantages of these alternative measures is that whilst conceptually demanding, they are quantitative and will allow the perceived issues to be discussed rationally.

This will be carried out by interviews with process owners and people who are active in the process. Ideally, this will include the customer of the process, or their closest representative within the organisation.

A horizontal audit of the process following a typical Entity will also show approximately what happens where in the process, even if the classes of resources used are general (may be disregarded for model simplification) and may be confused with the activities themselves. For each case study this is summarised in the section 1 of the chapter and the appendix.

5.3.2 Map manufacturing process

There is intended to be no confusion over the separation of activities and the resources used to carry them out. This is the principal objective of this activity. The IDEF₀ function block is most useful at this point, taking the horizontal audit from the previous section as a starting point. However, using IDEF₀ will not be an absolute requirement, as long as the potential entity routings are captured as process maps, the resources are all defined and the nature of the set of activities is understood.

For each case the case study is reported in section 2.1 of the case study appendix.

5.3.3 Produce Entity Activity Resource Definitions and cover set memberships

This process is carried out iteratively with section 5.3.2. The objective of this activity is to define what the entities, critical resources and definitive activities are in the process. This is done by:

- Entities as seen by the customer, including what is required from internal activity steps to realise them. It is the input to/output from the system, the thing that is transacted upon inside the system. For this reason, the transformation carried out by the activity might be on information or materials;
- Activities must form a complete set from end to end and have no overlap between them.

A critical issue with an activity definition is to ensure that it is fully independent of the resources that carry it out. The set of activities describing the process must be described completely (exhaustively) and each mutually exclusive transformation step with a single activity.

- Resources must belong to the same class – for example, it is not useful to decide that hand tools are the critical resource in one activity but that people possessing the right skill are critical to another. In practice, this is not a great constraint. Any disruption arising is attributed to a particular cause when a BREAKDOWN state is observed. To return to our example, if people are the reason for the breakdown then that is recorded when observing a server state, if it is the unavailability of hand tools then that will also be recorded. The critical question to ask is again “which other resources may be available to carry this out ?” and to look for the most involved or complicated results. Given the recurrent theme of standard operations in the lean literature, then people possessing the right skills will be the key resource throughout the studies.

Once these three sets are established, it is possible to use the process map to ensure that there is a mapping relation between at least one member of the Entity, Activity and Resource sets.

For each case study this is reported in section 2.2 of the appendix.

5.3.4 Aggregation of the manufacturing process into a set of critical queues and observable states

With the set hierarchies in place it is now appropriate to see how the process should be simplified by aggregating activities into a super set, which will then have different (but we are arguing not significantly so) relations mapping onto the resource set. This will not be done where the cover set of entities is affected.

Aside from simplifying the model as far as possible, the other aspect of this is to simplify the process of queue length and server state observations. For example, where a conveyor or single piece flow joins activities, there may be limited benefit from observing the dynamics of all of the queues because they will be slavishly linked to one another (though this will serve as a good illustration of transmission of complexity through closely coupled resources). For each case study this is reported in section 2.3 of the appendix.

The useful output of this step of the methodology will be a simplified process flow (as far as valuable) that supports the following step.

5.3.5 Entropy Study of the Entity Activity Resource system

The objective of this section is to gather observations of the queue and state changes of the activities in the process and calculate entropy values for each activity. Given the requirement for conventional measurement data (or throughput data if this is not measured in the process), then this should also be recorded for the period of the study. The observations should be made as follows:

- Enough observations to have a reasonable statistical set – confidence that this is typical operation of the system;
- Observations are to be made during a steady state of typical operation, not including long shut downs (requiring some ramp up and down in and out of them), frequent step events (such as tea breaks) and externally imposed “one-off” disruptions (such as a supplier going out of business). These will tend to show atypical states in terms of their occurrence and probability of occurrence. Whilst this does show what the range of behaviours of the system is like in all circumstances, it should not be at the expense of a solid set of observations of normal operations;
- To overcome the requirement for instantaneous samples of all activities (in order to exploit the property of Jackson networks), sampling in the reverse direction to the flow should be carried out.
- Sampling at a frequency that reflects the operational rate of the process. Sampling too frequently will be redundant and fail to provide coverage of the whole range of queue and server states within a reasonable sample size of observations. Sampling too infrequently will lengthen the elapsed time for the study and make other process “disruptions” more likely (see the point, above);
- When recording the queue length, the piece being worked upon should not be included;

- When recording the server state, a BREAKDOWN state should be annotated with what the cause of the breakdown is. Examples are:
 - Missing operator;
 - Unplanned downtime from broken/damaged equipment;
 - Missing/wrong parts at the server (not including the entity, whose absence constitutes an IDLE state, not a BREAKDOWN).

The data is collected in a paper form and transferred to a Microsoft Excel spreadsheet for calculation of its entropy values. Within the spreadsheet, the results of these queue and state observations are then tabulated by queue server. This is done to allow the probabilities of observing a particular queue and server state combination to be calculated. Two results are calculated (see Equation 4.7):

- A measure of pure obstacle to flow or each server, as calculated just from the observed range of queue lengths;
- An expanded measure showing the further division of probabilities into server state. This then also considers the relative contributions of server state to the obstruction to flow of each server.

Both of these are calculated by the expectation of the information of observing each queue server. Where queue lengths only are considered then the probabilities are simply those associated with observing the queue of particular lengths. Adding server states further splits the observed states, reducing the probabilities since the state is now also considered coincidentally with each queue length.

Once the two sets of probabilities are determined (with and without states), these are calculated using Equation 4.7. A full worked example of this calculation process for one of the case studies is available for the case study in Chapter 7 in Appendix section B.3.

The other critical output from this activity is the availability of the conventional measures for the same period of operation. This data is used to validate the framework, and is used in the activity described in section 5.3.9.

For the case studies, this is reported in chapter section 2.1.

5.3.6 Q-analysis of Entity Activity Resource cover sets geometry

The objective of the Q-analysis is to derive a description of the structure in terms of the relationships between the members of cover sets that have been designated as Entities, Activities or Resources. The mathematical technique is described in Section 4.5. It will provide the values for each set member:

- The *q-top* value of the dimension at which the set member first appears in the geometry *i.e.* how many other set member it is connected to;
- The *q-bottom* value of the dimension at which the set member joins a simplex with other set member *i.e.* shared connections;
- Its eccentricity – there will be two sets of these figures, one for each set in the relation under consideration.

These are all important measures from the Q-analysis, and they need to be considered when looking at the structure in question. A full worked example of this calculation process for one of the case studies is available for the case study in Chapter 7 in Appendix section B.4.1 for the incidence relation and B.4.2 for the Eccentricity calculation. For each case study this is summarised in chapter section 2.2.

5.3.7 Characterise flow behaviour based on Entropy measures

The objective of this activity is to review the entropy study results in isolation, to reveal the nature of the obstacles to flow from each queue server. This is done by reviewing queue-only

results (to see the process flow obstruction) and then reviewing results of with-states entropies (how each queue server is being obstructed).

Considering the with-state entropies in conjunction with the process routing also shows the potential transmission of disruption from one process to another. The with-state results show whether it is transmitted disruption or locally generated by either a local capacity limit or local operational problems such as a high proportion of flow obstruction from BREAKDOWN or SETUP states.

The outcome of this activity is that the locations and reasons for flow obstructions are known before the description of the structure is compared to the flow behaviour achieved from each server.

A discussion of flow and entropy is summarised in each case study in chapter section 2.1.

5.3.8 Compare Entropy and Q-analysis measures

The objective of this is to ascertain the circumstances (if any) under which the measures are actually mutually reinforcing and supportive or contradictory. Where the two distributions of without-states entropy and eccentricity seems actively similar or dissimilar, a correlation test may be appropriate, the significance of which may be verified by a nominal 95% confidence interval on a t-distribution test statistic. A significant correlation between eccentricity (equation 4.8) and entropy (equation 4.7) will imply that structure and flow obstruction are related, and that this may warrant closer investigation as to the causes of flow obstruction.

This is summarised in the case study chapter section 2.3.

5.3.9 Build a discrete event model to validate the framework and measures

This activity is summarised in section 3 of the case study chapters.

The preferred discrete event modelling tool is Simul8 2000 v6, from Simul8® Corporation. It is not the only tool that may be used, since many discrete event-modelling tools possess identical capabilities, including:

- a structured project format for working;
- a visual logic for constructing model entities and their interrelationships;
- programmable entity logic, including statistical distributions for cycle times, arrival rates *etc.*

With a great deal of the preparatory work completed in a consistent framework from earlier activities (problem definition, model entities, validation data from the system under study, identification of critical process steps and their queues, aggregation to a minimum useful set of entities) this modelling activity is greatly simplified.

Two forms of model validation are required – black box and white box. Black box validation seeks to ascertain that the input/output behaviour of the model is consistent with the actual system in question. White box validation seeks to ensure that the behaviour of model entities is reasonable and reflects their real world counterparts.

5.3.10 Make interventions on the model and consider process improvements

Using the validated discrete event model, it is possible to carry out experiments *in silico*. This will include changes that would have a recognisably different geometrical EAR hierarchical structure and/or attempt to reduce the obstacles to flow in the process by mitigating the bottlenecks creating the high entropies. Where the with-state entropy is indicating a particular cause, this may be the origin of a candidate fix.

If this final step is taken in the study, the implications for the prescription of operational effectiveness (usually via a tool or technique, but increasingly via a principle) must be considered.

Once this intervention is made *in silico*, and assuming a net improvement has been delivered, it may be decided to implement the change in the process via an intervention in the actual system. This will need to be a separate change project, but the actual results should be reported back to validate/assess the changes to the discrete event model from which the actual change was conceived.

5.4 Selecting the example processes to study

5.4.1 Taxonomy

The methodology will be used to test various degrees of sophistication of the model as applied to actual processes. The next three chapters discuss each of these and what may be concluded about the model as well as the insight into operational effectiveness from the use of the model on each process. Each study has been selected and designed so as to test different axes of sophistication.

The “axes” of the model are as follows:

- Which relationships and set memberships are of simultaneous interest in the study, and to what extent they will affect/constrain one another;
- Expected number of set members in each of the Entity (E), Activity (A) and Resources (R) cover sets;
- Expected nature of each of the three defined relationships R_{EA} , R_{AR} , R_{AA} ;
- Whether the flow in question is material, information or made up of both;
- The occurrence of “recursion” of systems within the system under study – this affecting the assumptions that will have to be made about any aggregation, and how definitions of entities may need to be modified between the systems.

5.4.2 Background to the Study Examples

All of the three studies were carried out at Linx Printing Technologies plc, a UK based manufacturer of industrial printing (coding and marking) equipment and consumables. The company operates on a multi-site basis, but all of the processes studied take place in the continuous inkjet printing business in St Ives, Cambridgeshire, UK. The printers and their inks and solvents are designed and manufactured in St Ives, and are then sold through distribution to forty counties worldwide. The St Ives business employs some 250 people and accounts for about two thirds' of Linx annual operating revenues of around fifty five million pounds (financial year 2003-04).

Linx was established in 1988 and since then has had numerous campaigns and programmes of operational effectiveness, particularly through lean manufacturing and its associated tools.

The St Ives business conducts the design and assembly of the printers. All proprietary components are bought from vendors and original Linx parts are made by subcontractors. The St Ives business also carries out the formulation and mixing of most inks and solvents (all raw materials and some specialist third party inks and solvents are manufactured by specialist suppliers). All inks and solvents are packaged in St Ives.

5.4.3 Characterisation of Business Processes investigated in Study Examples

The three study examples have been selected to test different parts of the product space of the taxonomy described above. Figure 5.2 summarises this.

Chapter	6	7	8
Brief synopsis	Single Piece Flow assembly of printers	Engineering Change Control	Ink and Solvent Delivery Business
Cover set hierarchy Relationship(s) of interest	R_{AR}	R_{AR}	R_{EA} and R_{AR}
Size of sets of interest (Number of agents)	Very Large	Small	Small
Anticipated complexity of considered relationships	Large	Small	Small
Nature of flow (materials, information, both)	Materials	Both	Both
Evidence of recursion of systems	None	None	Yes
Entity variety	None	Limited, known	Very Large

Figure 5.2 – Testing the product space of the methodology with case studies

Chapter 6 investigates a complex single relation in a relatively simplified greater system. Chapter 7 investigates a simple single relation in a more difficult environment of greater entity variety and the requirement to process information as well as material document entities. Chapter 8 investigates a simple system but looks at all of the relations simultaneously in a much more difficult environment. This latter case study also tests the definition of the Entity Activity Resource hierarchy with the use of a recursive subsystem, and the requirement to manage an interface between the Entity of the subsystem and the main process in focus of the study.

5.5 Conclusions

A sequence of activities for the application of the model developed in Chapter 4 in a prescriptive and repeatable fashion has been devised and described in this chapter. This addresses the second half of research question 5. By selecting three case studies, different types of process can be studied to verify the fitness of the model developed in support of this thesis. The selection of different set memberships in the EAR framework for the case studies also sets the scene to answer research question 6, pertaining to the use of the model in operational and strategic issues.

This chapter has been able to address research question 5, by showing how a complexity-influenced model can be made and its use operationalised. This is achieved using a novel framework of process system agents of interest, on which a pair of measures for patterns of complex system structure (Q-analysis) and flow behaviour (entropy).

CHAPTER 6 - SINGLE PIECE FLOW ASSEMBLY OF PRINTERS

6.1 Experimental Objectives

This chapter and the next two will test the viability of the complexity-influenced model and methodology developed in the previous two chapters in response to research question 5. These are designed to exploit the measures for structure and behaviour on the structure of agents proposed in response to research questions 4 and 3 respectively. The methodology is followed and finally the implications for the research questions of the case study are reviewed in section 6.5.

This case study will focus at the operational end of the spectrum proposed by research question 6, looking closely at "operational effectiveness" in a classic lean production environment with the complex system measures of entropy and structure.

This case study is a relatively large system (in terms of numbers of agents), and will be concerned with the Activity-Resource mapping relationship. The process is operating in a steady environment. This process spans just the manufacturing activities of the organisation, and is the core activity for all participants in the process. The individuals are dedicated to the process and its operations by following defined standard operations. This tests the "best practice" tool for lean manufacturing using single piece flow, to ascertain how the Activity-Resource mapping affects the most detailed levels of prescription of tasks being carried out in processes. There are empirically derived rules of thumb about this in use in industry, as described in the component parts of leanness.

The study is concerned with materials flow, where the Entity is a customer requirement for a printer, realised by the assembly and testing of printers through the process. Whilst there is variation in the range of products manufactured in this process, the variety has been carefully

managed by process design such that it is largely transparent to observer and participant alike in the single piece flow.

The axes of this study are shown in figure 6.1 (reproduced from Chapter 5):

Chapter	6	7	8
Brief synopsis	Single Piece Flow assembly of printers	Engineering Change Control	Ink and Solvent Delivery Business
Cover set hierarchy Relationship(s) of interest	R_{AR}	R_{AR}	R_{EA} and R_{AR}
Size of sets of interest (Number of agents)	Very Large	Small	Small
Anticipated complexity of considered relationships	Large	Small	Small
Nature of flow (materials, information, both)	Materials	Both	Both
Evidence of recursion of systems	None	None	Yes
Entity variety	None	Limited, known	Very Large

Figure 6.1 – Case study axes

The detailed background of the printer assembly process, including the derivation of hierarchical cover set membership, process mapping *etc.* is covered in Appendix A. An overview of this process is shown in figure 6.2:

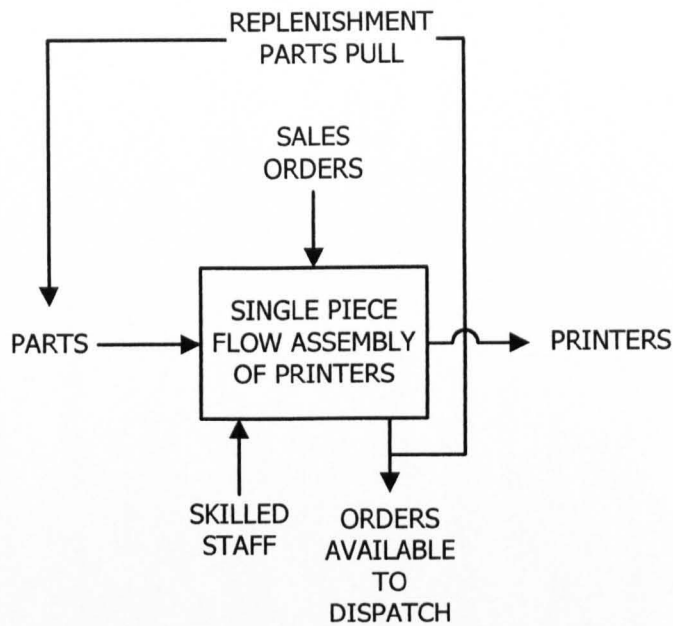


Figure 6.2 – IDEF₀ Single piece flow assembly of printers

This process summarises the assembly (Activities) of printers from parts, triggered by sales orders (Entities), carried out by skilled staff (Resources). This allows printers to be available to dispatch and triggers replenishment signals to pull parts.

This case study has been submitted to Decision Sciences Journal, as an illustration of the principal of joint measurements of complex manufacturing systems, co-authored with Frizelle, Johnson and le Moal.

6.2 Study results

A worked example for the case study in Chapter 7 is given in appendix B, in section B.3 for an entropy calculation and sections B.4.1 for Q-analysis and B.4.2 for Eccentricity calculation.

6.2.1 Entropy study

Data were collected by Jeremie le Moal, an IFMA (l'Institut Francais de Mechanique Avancee) student on his final year placement at Linx (working under the supervision of the researcher), as follows:

- Queue and state observations were carried out against the reverse of the flow process mapped in figure A.2. Data were collected five times a day at two hourly intervals, for the four working days (Monday to Thursday inclusive), for five weeks. The period included two national holidays, which were then three-day weeks. Between eighty and ninety data points were collected for each of the twenty-two activities in the process map, a total of 1852 observations on the system;
- Data was also collected to allow a simulation model based on the elements of the EAR framework discussed to be validated. This included system fill level (how many parts identified by works orders were live at any one time) and throughput time for a works order;
- Order arrival pattern for a number of months, to see if a stable demand exists, and if this is being managed via the lean principle of *heijunka* (schedule levelling).

As observed above the basic entropy measurement looks at the dynamics of queues formed by the activities. The indices reveal the following relative obstructions to flow throughout the process (see figure 6.3).

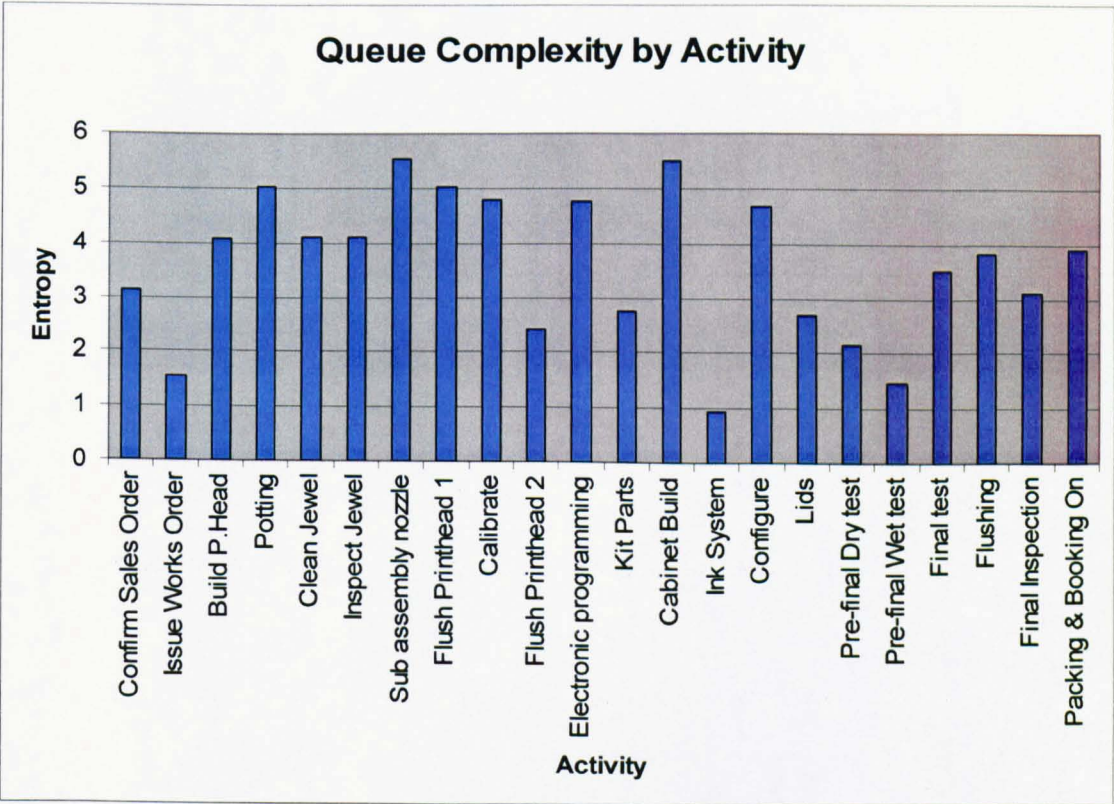


Figure 6.3 – Entropy without states for queues

Comparing Figure 6.3 to the process flow in Figure A.2 yields a number of comments concerning the flow from start to finish.

The entropy is consistently higher in the printhead manufacturing activities (from Building Printhead to Flush Printhead 2) than the printer assembly and test area (Kit Parts to Packing & Booking On).

Electronic Programming is a service activity feeding Configure and is performed on demand, staffed occasionally by electronics technicians who also undertake faultfinding and repair of printed circuit boards returned under warranty. Hence interrupted flow and high entropy may be expected from this particular activity.

Another comment that can be made is the activities described in Figure A.2 as "close coupled single piece flows" appear to show attenuated entropy with each subsequent activity step. This remains true when observed states are included in the total operational entropy calculation (shown in figure A.2)

To better understand the detailed causes of the obstacles to flow it is possible to look at the joint queue and resource state entropy, shown in Figure 6.4. As explained earlier, these latter comprise 'set up', 'downtime', 'busy' and 'idle'. The state 'unknown' was added for reasons already given.

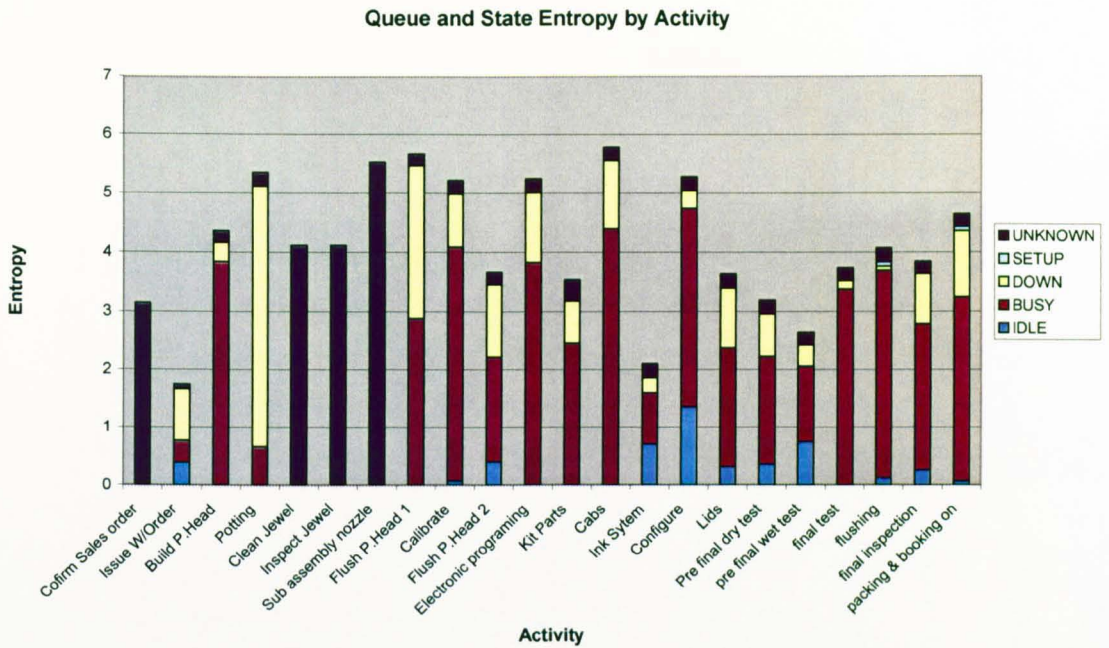


Figure 6.4 – Entropy measurements of queue and server states for the mapped process

The most significant finding is that Downtime states have added to the complexity of the process. The cause of Downtime was recorded where possible, and can be attributed to discontinuity in supply (an area of concern during the study), a shortage of available personnel, and batching behaviour. The shortage of parts from external suppliers and low inventory levels have caused a large number of stoppages even in those cases where the requisite skilled personnel were available. The exceptions to this are in the activities of skill 14 (Potting, Flush P.Head 1, Calibrate, Flush P.Head 2) and skill 4 (flushing) where upstream delays and localised batching behaviour respectively initiate and exacerbate Downtime. These will be discussed in some detail below.

Setup is a very minor contributor to the complexity in the system. This is indicative of a system where manual operations form the majority of activities.

For most activities there is a small proportion of unknown states, which is only a small factor of error or difference and was ignored. However in three cases (Confirm sales order, Clean Jewel, Inspect Jewel, and Subassembly nozzle) their resource states were wholly unknown. In this case the joint entropy takes the same value as the queue entropy.

Turning to the impact of Downtime, further investigation shows that the large proportion of Downtime states in the activities of skill 14 are the result of waiting for parts from the upstream feeding activity of printhead build (Skills 7/8/9), either through working practices or disturbances upstream. This is shown by the highest degree of Downtime in front of the potting process. Printhead build (7/8/9) has a high “busy” entropy component, indicating that it is always occupied, and as shown in figure 6.4, has reasonably complex queue dynamics. The absence of a contribution from Downtime implies a local bottleneck. Downstream practices in potting are exacerbating this local capacity constraint. The present practice is for operators to carry out the potting activity only once per day. Hence parts queue up in front of the workstation, waiting for an operator. This is the most extreme example of batching in a flow system designed as a single piece flow. The justification is that printheads are then left to cure for twenty-four hours, smoothing the waiting process. The result is that any variation in printhead build output is amplified and transmitted to the downstream processes in calibration. The other Calibration skill (14) processes following potting are all subject to swings in workload.

This manifests itself seen by Downtime as operators wait for the correct printheads for their customer (Configuration, skill 20), and overtime working to make up shortfalls. Unfortunately, the overtime working is out of synchronisation with Configuration. This, with a shortage of works orders, has introduced an extra obstacle to flow between ink systems (skill 3) and Lids (skill 1), as depicted in Figure 6.3.

Flushing (4) is designed to clean the fluid systems of tested printers, removing ink and solvent so that an as-new machine is installed on the customer’s site. Flushing is preceded by final test (15), which is a complete system test and soak of the printer in operation, including the production of test prints. There is a steady increase of entropy in these two processes. In final test (15) there is also evidence of batching, as operators will collect a number of printers from the process instead of one at a time. This has a knock-on effect in flushing (4) where swings from “famine to feast” are seen as the result of batching behaviour upstream. Hence a process operating at its upper capacity limit will show higher entropy in its queue dynamics (complexity)

in its busy state. This unofficial batching process operates outside of the system design, which was intended as single piece flow.

The very high entropy of the nozzle subassembly skill (12) is caused by batching and division of labour in the skill "cluster" developed around the clean room (10, 11,12) shown by Q-analysis. This is because there are constraints on movement between the clean room and other work areas and a fixed batch sizes/cycle time on the Clean Jewel activity (an ultrasonic bath). To minimise the downstream disruption of batching, high in-process inventories are maintained. This has been identified as an area for further improvement, but standard operations and equipment use will have to be redesigned to facilitate this.

Cabinets, Ink Systems, Configure and Lid Build (2,3,20,1) provide another interesting result. The very high entropy associated with Cabinet build shows that the preceding part kitting operation is not smoothing supply from stores. The ink systems (3) operation that follows has a lower entropy, as might be expected from the cell that follows immediately on from Cabinet build. Configuration follows, and here the part-built machines are fitted with a PCB and customised to a specific works order. The causes of high entropy seen here are:

- Delays and disruption created by reworking and queue shuffling to reconcile late sales orders to the hedging process carried out by the management team.
- Large inventory (queue) variations are caused by overtime (out of hours) working of the upstream calibration process, which is not synchronised to the rest of the plant.

After the complexity has been attenuated at Configuration, the entropy remains low until the machines go into their final test (15). This does show that, despite two sources of complexity at the start and middle of the process, the single piece flow works well in this area and hence there is a toleration of the idle states seen. The obvious penalty is that excess capacity is required to deliver the printers given these disruptions.

6.2.2 Q-Analysis

Using the skills matrix in Figure 6.5, the Q-analysis was completed for both operators and their skills. This skills matrix was obtained from the production supervisor, who uses it as his basis for training records and allocating operators to activities. It is therefore critical in the decision making process of resource allocation. No heuristics or measures were in use for how it is used or how it is to be developed *i.e.* skills distributed within the set of operators.

Skill	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22
Person																						
1															1	1	1					
2																1						
3	1	1		1																1		
4			1																			
5		1																				
6	1	1			1	1				1	1	1										
7																		1				
8								1	1													
9																1						
10										1									1	1		
11									1													
12		1																				
13				1						1	1	1										
14							1	1	1													
15														1		1	1					
16															1					1		
17								1	1													
18	1			1			1	1	1													
19	1																					
20									1	1	1											
21			1	1	1	1	1	1	1													
22		1	1																			
23		1												1	1		1			1		
24	1		1																			
25	1															1	1	1				
26							1	1	1													
27																						
28							1	1	1						1							
29									1	1	1	1										
30			1																			
31																1						
32	1		1	1																		
33	1			1		1																
34		1																				
35		1																				
36	1	1	1	1	1	1														1		
37															1							
38		1													1							
39			1														1	1	1			
40	1	1		1	1	1	1	1	1													
41										1	1	1	1	1								
42							1	1	1													
43				1					1													
44							1	1	1						1							
45															1	1	1	1				
46	1	1	1	1	1	1																
47	1																					
48																						
49																			1		1	1
50															1							
51			1						1													
52		1		1																1		
53																						
54				1						1	1	1										
55	1			1	1	1																
56															1							
57		1	1	1	1	1	1	1	1													
58							1	1	1													
59																						
60			1																			

Figure 6.5 – Incidence matrix for the R_{AR} relation: skills matrix for printer and printhead assembly and test. Operators' names have been removed.

A Q-analysis of the relation and its transpose, enabling two structures to be created. Taking operators first:

Q-level	Operator
7	{40},{57}
6	{6},{21,57,40},{36}
5	{6},{21,40,57},{25},{36,46}
4	{6},{18,40,21,36,46,57},{23},{25},{41},{55}
3	{3,36,6,21,40,46,55,57,18},{13,54},{23},{25},{29},{39},{41},{44},{45},{49} {1,25,18,40,14,21,26,28,42,44,57,58,3,6,33,36,46,55,52,13,29,41,54,32,20},{10},
2	{15},{23},{38},{39},{45},{49}
1	{1,15,23,25,39,45,3,16,36,38,52,8,14,17,18,21,26,28,40,42,44,57,58,41,6,32,33,46, 55,22,24,43,13,20,29,54},{10},{49}
0	{All}

Figure 6.6 – Operator Q-analysis

As can be verified by a cursory review of the skills matrix in figure 6.5, having at least one common skill connects all operators. More interestingly, and less obviously, is the high level emergence of a cluster of highly skilled operators sharing a large number of skills in Figure 6.6. This means that the most highly skilled people tend all to have a shared skills base. This begs the question that this may be a missed opportunity to develop separate centres of skill excellence for such “star” operators, or that a set of core skills (4 to 9 inclusive) are attained as part of an orientation process.

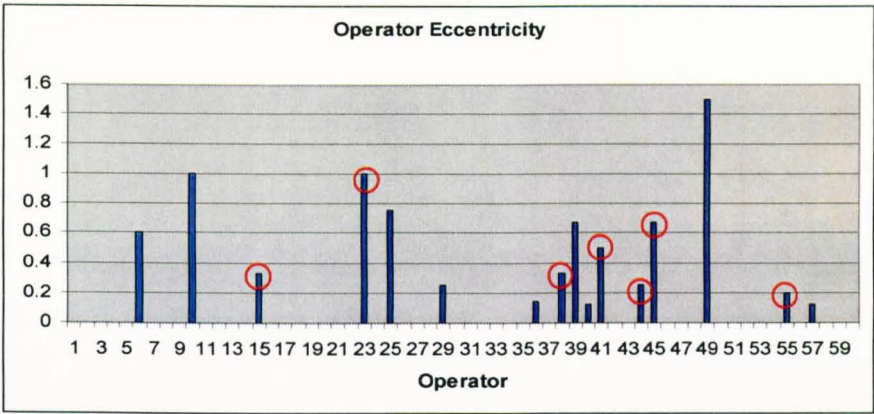


Figure 6.7 – Operator Eccentricity

Looking at absolute eccentricity in Figure 6.7, the most extreme eccentricity here is the operator 49 who is still qualified to build the laser *i.e.* skills 20 and 21, and given that this is a redundant process, may be considered a rogue result. Operators 15, 23, 38, 41, 44, 45 and 55 all possess skill 14, and all have high eccentricity, *i.e.* they are not well integrated to other operators in terms of shared skills. The other interesting result is that the remainder of the operators who hold that skill have zero eccentricity because they do not hold any other skills. This also highlights that the eccentricity measure is a useful indicator, but that additional interpretation of the connection geometry is always of benefit. This may be contrasted against the clusters of operators who are both well integrated and widely skilled within in the structure. Going on to consider skills:

Q-level	Skill
17	{9}
16	{9}
15	{9}
14	{9}
13	{2},{4},{9}
12	{1},{2},{4},{8,9}
11	{1},{2},{3},{4},{8,9}
10	{1},{2},{3},{4},{8,9},{14}
9	{1},{2},{3},{4},{7,8,9},{14}
8	{1},{2},{3},{4},{7,8,9},{14}
7	{1,4},{2},{3},{6},{7,8,9},{14},{15}
6	{1,4,6,5},{2},{3},{7,8,9},{10},{14},{15},{16}
5	{1,4,6,2,5},{3},{7,8,9},{10,11},{14},{15},{16},{20}
4	{1,2,4,5,6,3,9,7,8},{10,11,12},{14},{15},{16},{17},{20}
3	{1,2,3,4,5,6,20,7,8,9},{10,11,12},{14},{15},{16,17}
2	{1,2,3,4,5,6,8,9,20,7},{10,11,12},{14},{15,16,17},{18},{19}
1	{1,2,3,4,5,6,7,8,9,20,14,10,11,12,15,13,16,17},{18},{19}
0	{All}

Figure 6.8 – Skill Q-Analysis

Items emerging at low level in the structure will be less robustly resourced, and they are immediately identified by this analysis. In Figure 6.8 all skills have at least one person able to perform it, a re-phrasing of the earlier result that at least one skill connects all operators. This is a reassurance that (excluding the obsolete skills 20 and 21), there are no separate islands of skill at the lowest level, where loss/unavailability of a single operator would remove the capability altogether from the organisation. The analysis also shows that there are two principal patterns in the structure:

- High-level emergence of clusters of adjacent skills (refer to figure A.2), shown by the equivalence classes {7, 8, 9} and {10, 11, 12}. These indicate that in parts there is widespread upstream and downstream sharing of knowledge and experience in some of the process;
- There are also some highly eccentric skills (see figure 6.9), which are widely possessed but do not join an equivalence class with another skill until a low level. The principal example is skill 14, but others exist. This implies that the sharing of adjacent skills and people described above is not widespread in the entire skill structure.

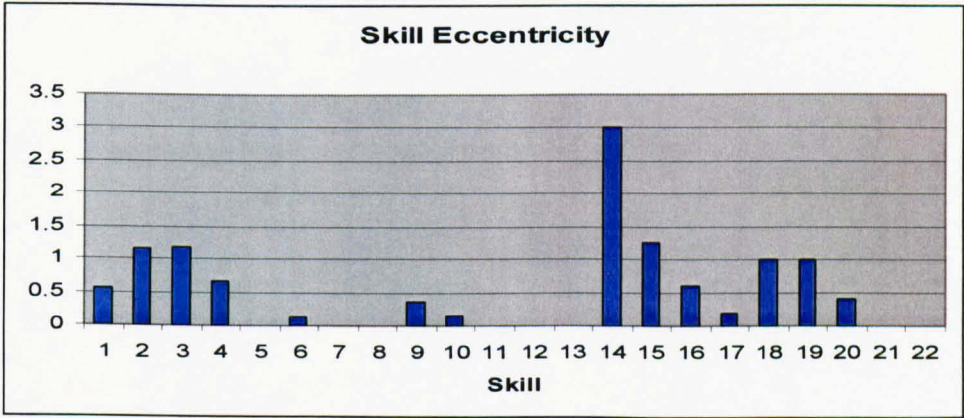


Figure 6.9 – Skill Eccentricity

A large number of the skills have zero eccentricity *i.e.* they are fully integrated with other skills into complexes at the level of which they appear in the structure.

6.2.3 Comparison of Entropy Measure with Q-Analysis

Given that queue complexities are additive, the contribution of each skill to flow obstruction can be seen. Grouping this by the skill set from which the activities are resourced, and comparing with the eccentricity results for the skill set in figure 6.9, we see the following (Fig. 6.10):

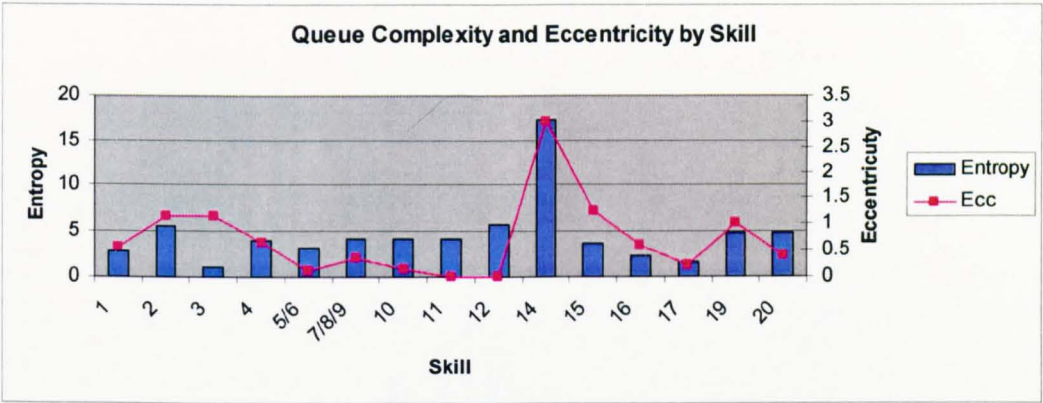


Figure 6.10 – Entropy from Queue complexity and Eccentricity compared

It needs to be noted that skills 7,8 and 9 are all represented by one process in the map (and entropy observations), and the eccentricity value taken is for skill 9 (Skills 7 and 8 have zero eccentricity). The same is also true of 5 and 6, (PR and PH respectively) which denote the final inspection of printers and spare print heads.

This figure shows the interesting result that the processes with the higher eccentricity can also exhibit a high level of complexity. Skill 14 (with the particularly high eccentricity) accounts for the largest single queue complexity result, and is a contributory factor in the disruption of Configuration (20).

Taking all skills as a set, there is a positive correlation of $r = 0.75$ between the absolute Eccentricity and Entropy of Queue Complexity. A t-distribution test statistic is 6.18. For this data set of 15 points, $t_{2.5,13} = 2.16$, and hence we can conclude that this is a significant result at a 95% confidence level. To elaborate on the correlation figure, additional value is to be derived

from looking at significant positive and negative examples of correlation between the Entropy and Eccentricity.

In specific cases there appears to be good agreement between the observed Entropy and Eccentricity *i.e.* how separated the operators are from one another as a proportion of their overall skill level in the range of skills in the manufacturing area. The implication is that when skills are polarised, process performance suffers. Skill 14 (Calibration) has been an activity carried out by technician trained operators, who have traditionally had a great deal of discretion to take a printhead from its as-assembled state until it is ready to install onto a printer. The sizeable obstacle to flow (Queue Entropy) would appear to concur with the perception of this area as being a bottleneck, given the degree of overtime worked compared to the rest of the process.

The high eccentricity is a potential contributory factor to the obstacle to flow not being more transparent to the operators and management. Returning to figure 6.8, we see that whilst Calibration (14) emerges at very high level (Q-level of 10, eleven operators possess the skill), it only starts to appear in an equivalence class with either of the two feeding sub-processes {7,8,9} or {10,11,12} at a Q-level of 1. Hence the Calibration skill is highly eccentric to the skills adjacent to it, and the operators involved have different experiences of the same interface between standard operations.

An example of the negative correlation is ink systems (skill 3), which has very low queue entropy, but a relatively high eccentricity. In fact, its relative eccentricity to adjacent activities (supplier is cabinet build, skill 2 and customer is configuration, skill 20) are also high, being 1.17 and 1.6 respectively. A possible explanation is that the flow is intentionally close coupled between both of these activities, so that fewer opportunities for obstacles to flow are possible.

Another negative example is the configuration (skill 20), which has a low eccentricity but high entropy. The supplier / customer relative eccentricities are 1.6, 3, 3, and 1.8 for skills 3, 14, 19 and 1 respectively. These relative eccentricities are also higher than the absolute eccentricity for

the skill. The reasons for the obstacle to flow from the upstream activities here have been described.

6.3 Modelling

A model was made in the Simul8 software by Jeremie le Moal, following the process defined in figure A.2. This is shown in figure 6.11.

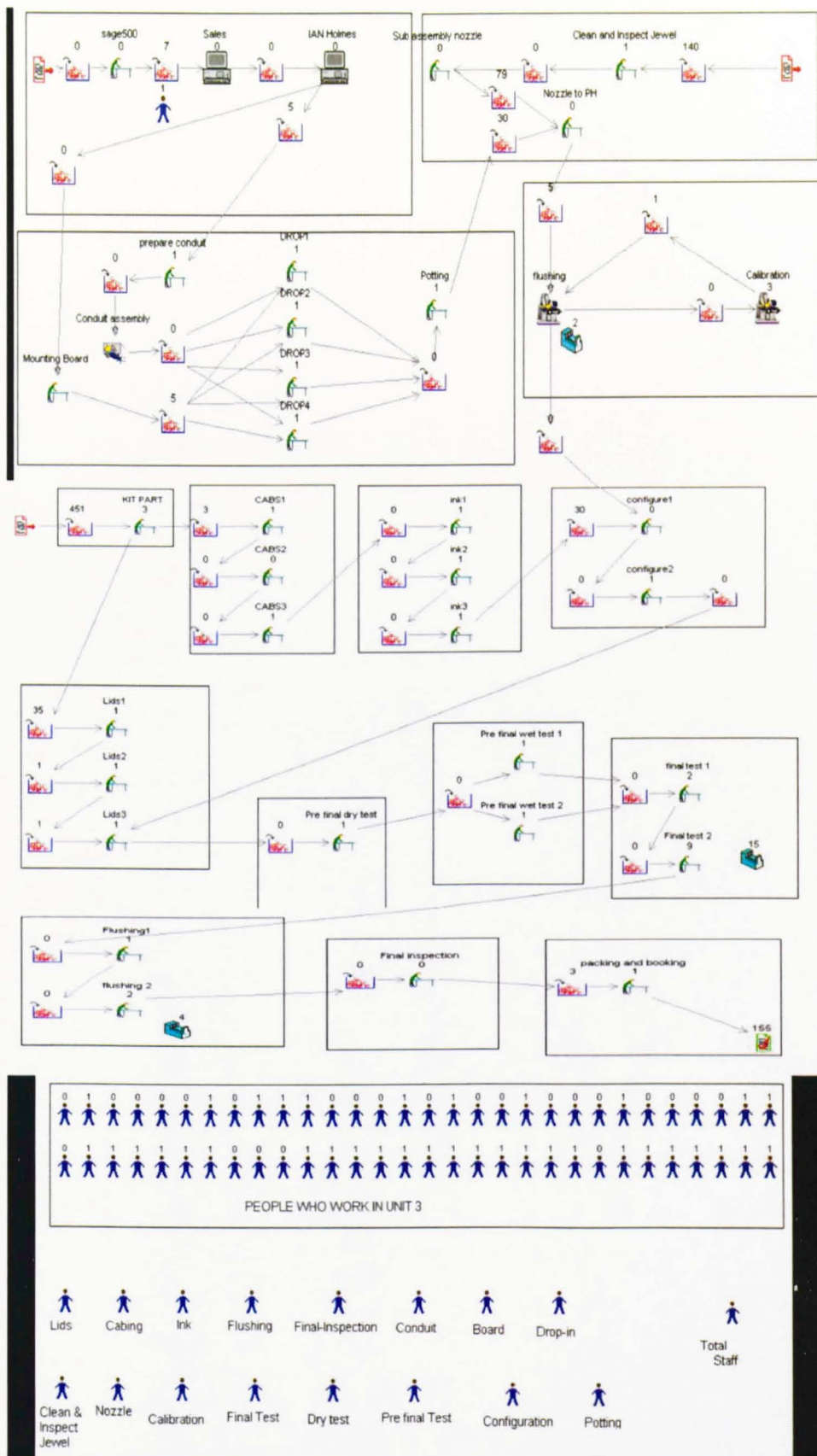


Figure 6.11 – Simul8 representation of the printer manufacturing process

The model used an arrival pattern for sales orders based on an analysis of nine month’s data from September 2002 to June 2003, amounting to 84 sessions of communication. The agreement between the sales order processing group and production planner is that the sales orders will be sent to production twice weekly, on Tuesday and Thursday, and that this will be for a nominal fifty machines per session. The reality is that sales orders are typically 0.9 days late, with a standard deviation of 0.5 days. The average quantity per session is actually 41.8 printers, with a standard deviation of 21.6 printers. This shows that all ideas of a level schedule in production are impossible.

A model was then built using the EAR framework as described, for the statistical arrival pattern seen in the period described above. This model was then validated for the nominal values of the production system, based on following works orders through the system. Because the data collection of the study was only for five weeks, the small number of figures per metric was averaged. Once constructed, the model was replicated twenty times, and key performance data collected, as shown in Figure 6.12.

	System fill level (Printer works orders)	Throughput time (mins)	No. Printheads output per week
A = Actual average (nominal observed)	40	1650	160
B = Model average (20 replications)	39.65	1416.2	160.15
Model St Dev (20 replications)	5.314	29.39	3.167
$B \div A \times 100 =$ % agreement on average	99.1%	83.5%	100.1%

Figure 6.12 – Model results for validation

To test the actual significance of the model output the following large sample two-tailed significance tests at 95% were carried out using estimates of the population standard deviation. For the system fill level and number of printheads output per week, it was possible to conclude that at the 95% level that the mean of the model operation was within the population of the actual system. It was not possible to conclude this for the throughput time, which nonetheless is relatively close at 83.5%.

The agreement between the model and the actual system is on balance very good, and reflects the validity of the choice of Entity, Activity and Resource definition. Modelling based on the set definitions of the EAR framework decided for the case study would therefore appear to make a useful contribution to validating the results of the measurement and analysis based on the two measures of complexity. This is because it produces similar behaviour to the observations of the actual system.

6.4 Conclusions and discussion

6.4.1 The relationship between flow and the Activity-Resource relationship R_{AR}

The case study has shown that whilst the company has pursued the “best practice” of skills definition in standard operations that are assessed, it has taken a binary approach to having a skill (or not). Skills have been “locally” developed into cellular clusters in parts of the process, and left eccentric to one another in other cases. It is unclear whether this is by design or not.

It is concluded that structural disconnection identified by Q-analysis may contribute to interruptions to flow behaviour, of which the entropy is a good measure. Whilst it is not the only cause of obstacles to flow in processes, there are examples in this case study where disconnectedness of adjacent activities accompanies high entropy.

In order to improve flow efficacy via entropy reduction, as proposed by Frizelle and Suhov (2001), within the process, it may be possible to “design” a structure of skill distribution in a workforce. Q-analysis could then be used to maximise flow with a given set of resources (operators). However, it must also be noted that the relationship shown (mapping resources – operators - onto activities defined by a skills matrix) is not the only driver of high entropy in the behaviour of queue servers such as the activities studied here. For this reason Entropy is a powerful tool because it is an objective, additive measure of flow behaviour, and it can be expanded to include analysis of the states of the queue server, providing insight into the causes of the obstacles to

flow. The R_{AR} relationship was not the only cause of flow obstruction in this case study, there also being a contribution from supply chain disruption.

Entropy and Q-analysis used together will be able to identify the flow obstacles that are structurally induced, or more likely in less robust structures. This robustness and structural fitness needs to be better defined. In this case study, it appears to be the maximising of shared operators between adjacent activities/skills, coupled with strict adherence of the design rules of single piece flow.

This study has been a first attempt at deriving the actual relationships between skill distribution in a process and the established rules of thumb used in the manufacturing community *i.e.* how structure drives and influences behaviour. Further development could include modelling to test how improvements might be "designed" using entropy reduction as a goal. It may then be possible to explain the existing rules or develop new rules of thumb for the adoption of the standard operation and other practices in lean production systems.

6.4.2 The effectiveness of joint measurement for process improvement and stakeholder issues

The stakeholder issues were identified as being:

- *An improved understanding of flow obstruction.* It would appear that some disruption is caused by internal disturbance from the late deliveries of upstream supply. More interestingly, this study was able to identify two examples of internally propagated disturbance. This is felt to be more interesting because it is both more significant than late delivery from suppliers (the contribution to queue entropies shows this), but was also not suggested by any of the stakeholders interviewed. In both cases where this was observed, it was the result of batching from upstream processes that was starving downstream processes. This was witnessed by a combination of IDLE and BUSY states. As a direct result of this study, a pair of Visual Management (VM) boards was implemented at the flushing (skill 4) and calibration (skill 14) resources (one of which

was the subject of the allegations associated with their excessive overtime working). The boards were able to show (after the conclusion of any data collection connected with the study), that there were periods of time in the working week when there were no products available. See figures 6.13 and 6.14 for examples. The manufacturing engineer in the study, PE, has now turned his attention to the redesign of both the triggering mechanisms and the processes itself, especially the potting operation in front of the printhead flushing and calibration;

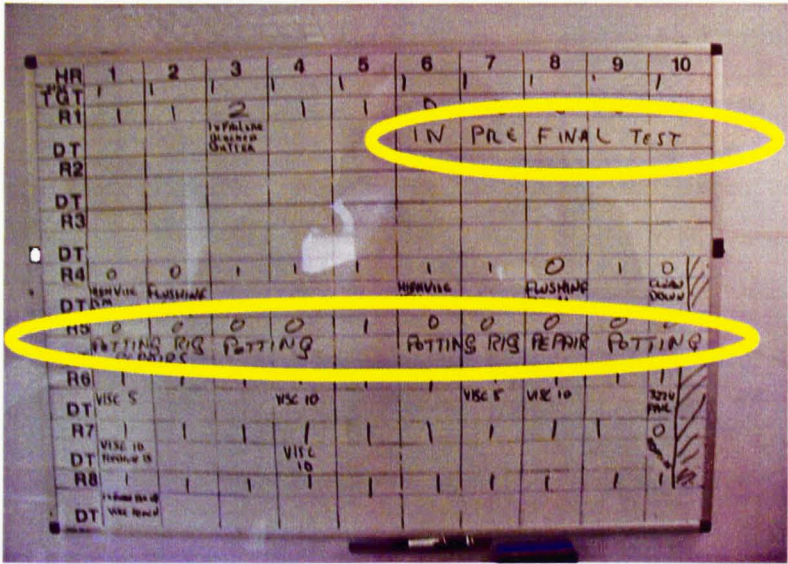


Figure 6.13 – Calibration VM board (taken 12th August 2004), showing certain operators involved in supporting Breakdown states at other activities when no other work was available in the Calibration area (highlighted on the boards)

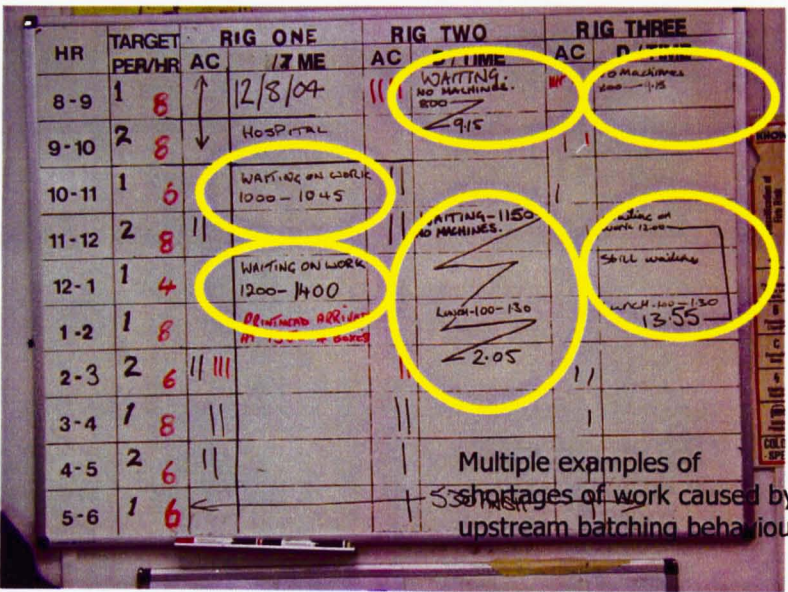


Figure 6.14 – flushing VM board (taken 12th August 2004), showing multiple examples of shortages of work caused by upstream batching behaviour (highlighted on the boards)

- *A measure of the characteristic nature of skills dispersion.* The study has been able to show that flow obstructions (their causes not understood clearly, as shown above) can be associated with structural disconnects in the geometry of skills sharing amongst operators. In addition to gaining real insight into the causes and seriousness of flow obstructions in operation with entropy, the study suggests that the measurement of skills dispersion is useful. It would not be unreasonable to expect that greater mutual understanding of adjacent processes would yield less suspicion and unsupported opinion as to the causes of flow obstructions, and similarly that it would assist internal supplier-customer quality relationships;
- *The impact of late arrival of orders on the system.* The study has shown that this is being mitigated effectively by the excess capacity in the production system itself. Any attempts to become leaner by reducing some of the resources from the system would reduce the ability of the operation to accommodate such erratic arrival and order quantity variation. The mix of products was not investigated (see comments on aggregation in section A.2.3) and this appears to be a reasonable assumption for the study. As the operation becomes leaner, it is likely that mix sensitivity will increase. Given the excess of capacity at the present time, this was not considered to be a priority for the modelling exercise.

6.5 Implications for the research questions

This study has successfully shown that the skill dispersion in an organisation (the geometry of relationship R_{AR} in agent terms) may be adversely affecting flow behaviour (measured by entropy of resources carrying out activities) and that these measures pertain to the agent level. In this section it will be shown that this could not be so clearly shown through the use of existing "operational effectiveness" tools.

Research Question 3

The R_{AR} relation defined the agents of interest as printers output against confirmed sales orders (Entities), standard work operations (Activities) and skilled operators (Resources). An accurate simulation model supported this relational framework. In this simulation conventional measures were repeatably reproduced using model elements derived from the framework, and so the EAR framework was shown to be an accurate representation of the system under study.

Research Question 4

The insight from looking at patterns of complex structure and behaviour was greater than that which would have been possible from conventional lean tools. Value stream mapping of the process would have mapped staffing levels, inventory, typical yield performance and cycles times for the process steps. Taken repeatedly at different times, it would have produced different impressions of the process studied, but repeat mapping only adds a range of observed behaviours, does not provide any explanation of the behaviour being observed and mapped. In contrast with this, entropy measurement shows the relative impact on the total process from flow obstructions (with causes) at each resource carrying out an activity.

Another lean technique called Visual Management (VM) uses boards at the workplace to monitor flow against demand driven targets. Their subsequent use in the process (see figures 6.13 and 6.14) only partially remedies the shortcoming of the higher-level techniques of value stream mapping. It does not, however, provide a system wide indicator of real flow obstruction resulting from each process step, where entropy provides a definitive numerical measure. Nor does it show the interaction of parts of the process on one another, either through flow or structural mapping of shared operators *i.e.* skills dispersion, as shown by the geometry of the R_{AR} relation.

Research Question 5

The model was successfully applied in a crisply defined environment of easily recognisable sets of entities, activities and resources. As discussed above, deeper insights than would be available from using lean tools in isolation were available from the use of a complexity-influenced model.

Research Question 6

This was a highly operational case study only, and whilst strategic issues were not encompassed in the brief for the study, it supports the assertion of this thesis.

Research Question 7

Absolute excellence may be shown from this case study to be a skills dispersion that produces flow without any obstacles, i.e. the achievement of the minimum cycle time without waiting in queues. This case study provided some evidence that skills' "clustering" is not conducive to good flow. This definition of absolute excellence is restricted to flow efficacy and does not consider other strategic objectives that may be requisite (not discussed in this study, which was very operational in nature - see research question 6, above).

CHAPTER 7 - ENGINEERING CHANGE CONTROL

7.1 Experimental Objectives

Chapter 6 was able to show an example of a manufacturing system about which very operational study questions were being posed. The agents of interest in this system were defined, and were consistent with complex systems view of the system. A pair of measures of behaviour and structure (Entropy and Q-analysis) were used, operationalised in methodology. Their use identified operational effectiveness of a system as geometry of skill (Activity) dispersion in Resources (determined by a matrix of standard work) that is consistent with no obstruction to flow of entities. The results of the study demonstrated that the insights provided could not have been obtained by the exclusive use of the tools of current "operational effectiveness" (in this case value stream mapping and visual management).

To further develop the thesis, this chapter will look at another system in which both information and materials are processed. Crisp mapping of resources onto activities is not available for the following reasons:

- The systems resources are not all exclusively employed by the process (anyone employed at the company can be given actions) and it is "another" thing to do in their jobs;
- The nature of the work (implementing change) does not readily lend itself to work standards;
- The mapping of resources to activities is better expressed as the activity content of different job descriptions.

The objective of the case study is to test the model and methodology under the set of conditions described in figure 7.1. This is an operational system in a process where operational effectiveness" tools are less widespread (with notable exceptions in Murman *et al*, 2002; Costanza, 1996). As is discussed in Appendix B and throughout this chapter, the motivation from stakeholders in supporting this case study was that improved performance should be possible in this process. This chapter demonstrates that this improvement was possible.

This case study is a relatively simple system, and will again be concerned with the Activity-Resource mapping relationship. The process is operating in a slightly more turbulent but largely known environment compared to the previous case study. This process spans an entire organisation, but is only a core activity for a very small proportion of the participants in the process. The individuals are not dedicated to the process and its activities in the same way that standard operations were defined in the previous case study. This tests the more loose management of a process, to see if the Activity-Resource mapping is still relevant at a more granular level of study aggregation.

The study is also concerned with both the flow and transformation of both information and materials, where the Entity is a requirement for a change to the specification of a product, including printers, inks, accessories, spares kits, technical documentation and marketing materials. These changes are codified and managed through Engineering Change Notes (ECNs), which are paper forms.

This case study is one in which an active intervention was first modelled and then made in the actual system, changing the R_{AR} relation by changes to the job definitions of key operatives. The axes of this study are shown in figure 7.1 (reproduced from Chapter 5):

Chapter	6	7	8
Brief synopsis	Single Piece Flow assembly of printers	Engineering Change Control	Ink and Solvent Delivery Business
Cover set hierarchy Relationship(s) of interest	R_{AR}	R_{AR}	R_{EA} and R_{AR}
Size of sets of interest (Number of agents)	Very Large	Small	Small
Anticipated complexity of considered relationships	Large	Small	Small
Nature of flow (materials, information, both)	Materials	Both	Both
Evidence of recursion of systems	None	None	Yes
Entity variety	None	Limited, known	Very Large

Figure 7.1 – Case study axes

Full details of the background to the process, the identification of stakeholders and their issues, the derivation a cover set hierarchy membership and an aggregated process is given in Appendix B, with an overview below. The process formats, reviews and implements engineering change in the products and documentation of the company. This was a process in difficulty at the time of the study, and was failing to meet the requirements and expectations of the broader business. An overview is shown in figure 7.2.

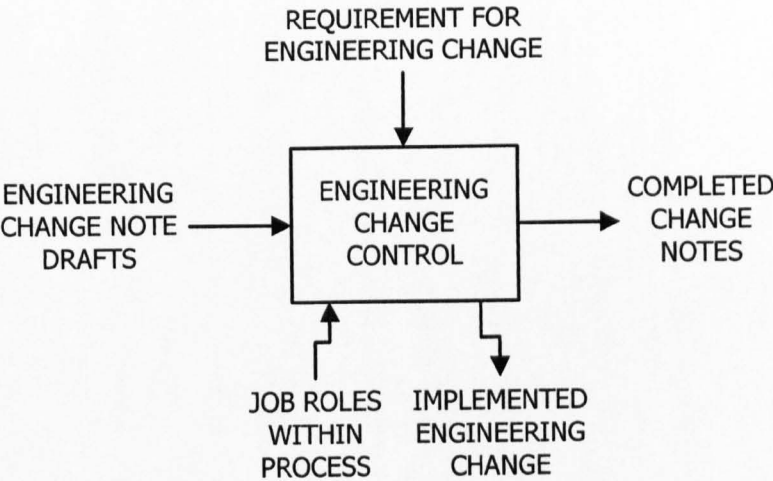


Figure 7.2 – IDEF₀ function block for Engineering Change Control

7.2 Study results

A worked example for the case study in Chapter 7 is given in appendix B, in section B.3 for an entropy calculation and sections B.4.1 for Q-analysis and B.4.2 for Eccentricity calculation.

7.2.1 Entropy study

Data was collected by Alae Oubella, an IFMA (l'Institut Francais de Mechanique Avancee) student on final year placement at Linx (working under the supervision of the researcher), as follows:

- Twice-daily observation of queue and state behaviour or a cross section of participants in the ECN system at the time of the study. This was carried out for around four weeks, producing around 200 observations. Unfortunately, the average historical ECN

throughput time at the time of the study is twelve weeks, and it was not possible to collect data for this length of time;

- Summary analysis of ECN flow behaviour in the company over a period of years, creating a historical analysis based on around one and a half thousand separate ECN transactions.

The results are summarised in figure 7.3.

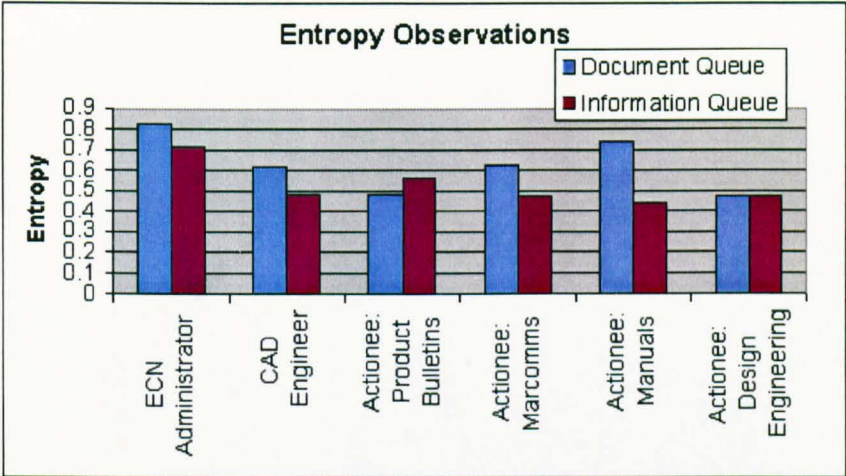


Figure 7.3 – Entropy without states for both document (material) and information queues

Both types of queues were studied because it emerged through discussions and interviews with stakeholders that there is a lot of waiting for information from other sources to enable them to carry out their own action. Observing both types of queue showed the real causes of obstructions to flow, which in both queuing systems was revealed to be the ECN Administrator.

The only exceptions were the Product Bulletins actionee, who it seems is a net exporter of information and hence entropy to the other participants in the process. The Design Engineering actionee, is also unaffected by others in the design changes they have to make. The manuals actionee is most affected, but this is because of a lengthy approvals process for any addition to the company’s technical product literature.

In both queue observation scenarios, the clear result is that the ECN administrator has the highest entropy, and therefore contributes the greatest obstacle to flow. This is despite his ability to work exclusively on ECN’s. This will manifest itself in all of the activities that he carries out.

The entropy with states results are not presented in this case because such a small proportion of the reported states were MAKE concerned with ECN’s (it has been stated that the serving the ECN process is far from a full time role for most of the resources).

7.2.2 Q-analysis of R_{AR} relationship

The Q-analysis looks at the structure of the entire process, and necessarily includes resources not included in the Entropy study (Committee and Purchasing). The matrix for this relationship R_{AR} is as shown in figure 7.4.

	ECN Entry	Review at committee	Investigate implementation	Assign Actions	Complete Actions	Track Actions	Implement Change
ECN Administrator	1	1	0	1	0	1	1
Purchasing	0	0	1	0	1	0	1
Actionees	0	0	0	0	1	0	0
CAD Engineer	0	0	0	0	1	0	0
Committee	0	1	0	0	0	0	0

Figure 7.4 – Mapping relationship R_{AR} between Activities and Resources

Q-Level	Participant
4	{ECN Administrator}
3	{ECN Administrator}
2	{ECN Administrator}, {Purchasing}
1	{ECN Administrator}, {Purchasing}
0	{All}

Figure 7.5 – Resource (role) Q-analysis for R_{AR}

Participant	ECN Administrator	Purchasing	Actionees	CAD Engineer	Committee
Eccentricity	4	2	0	0	0

Figure 7.6 – Resource (role) Eccentricity for R_{AR}

Figures 7.5 shows that the ECN Administrator (despite being present in many of the key steps of the process), has the highest overall eccentricity result (see figure 7.6). The ECN Administrator is

not well integrated into the structure of the complex created by this process, because it has a low level of shared connection with other resources. The ECN Administrator is however still highly connected. Purchasing shows a similar result, being active in three Activities, but only sharing one Activity with one other Resource (the ECN Administrator).

Unlike the previous study, where the Activity is a precisely defined standard operation, the work content is highly variable in each of these steps, depending upon the nature of the change. Also, the connection of Resources through a shared Activity does not imply that the same task is being carried out; rather that the work content of that Activity requires input from the aforementioned roles. The implication of the connection is therefore different, as the skills are not "shared" in the same way by the connection at a particular Activity.

The mapping of Activities to Resources in this case study is therefore the definition of jobs within the process steps. The high Q-top level of connection of the ECN Administrator indicates that the ECN Administrator role is present in most Activities, with the exception of carrying out actions. The connected structure shows that the common link of everyone to the process is the ECN Administrator as a consequence of this. The Q-bottom values of all other Resources show that the connection to the process is through the ECN Administrator and hence that they have a single point of contact with the rest of the structure.

Significantly, all drawing changes carried out (as an action) by the Engineering Services Group (ESG) are carried out by the ESG CAD Engineer, and so there is an additional queue server created within ESG.

7.2.3 Comparison of Entropy and Q-analysis measures for the R_{AR} relation

Given the available data from the study, it was not possible to conduct a correlation and t-test. However, an inspection of the entropy and eccentricity does show that the ECN administration role carries both the highest eccentricity in structure and information (and less importantly,

document) queue entropy. Given this fact, an intervention based on a redesign of this role with the available resources was then investigated, as described below.

7.3 Modelling

7.3.1 Model construction and validation

A model was made in the Arena software by Alae Oubella, based on the simplified process shown in figure 7.7.

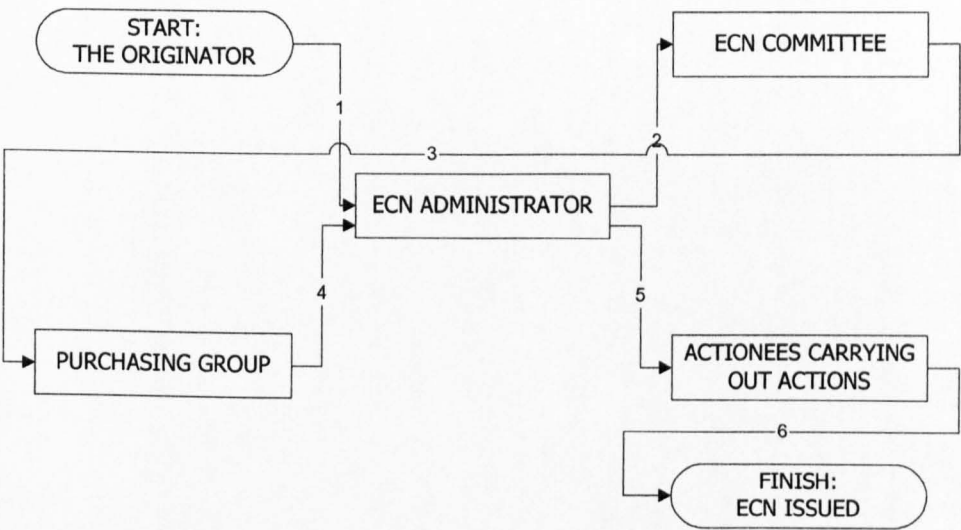


Figure 7.7 – ECN Process modelled as a series of flows (sequence as number label on arrow) through model resources.

The throughput times for the different types of ECN were then defined as distributions, and the process modelled in the Arena software. A screen image is shown in figure 7.8.

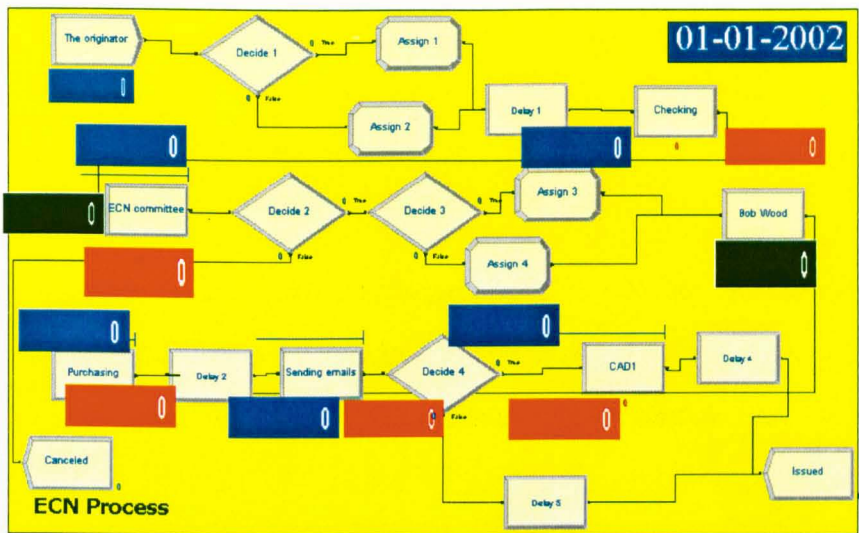


Figure 7.8 – Arena representation of the ECN process

The results of the ten replications of the model against the actual are shown in figure 7.9, for both average arrival rate and time spent by ECNs in the process. Each represented one-year’s operation of the process.

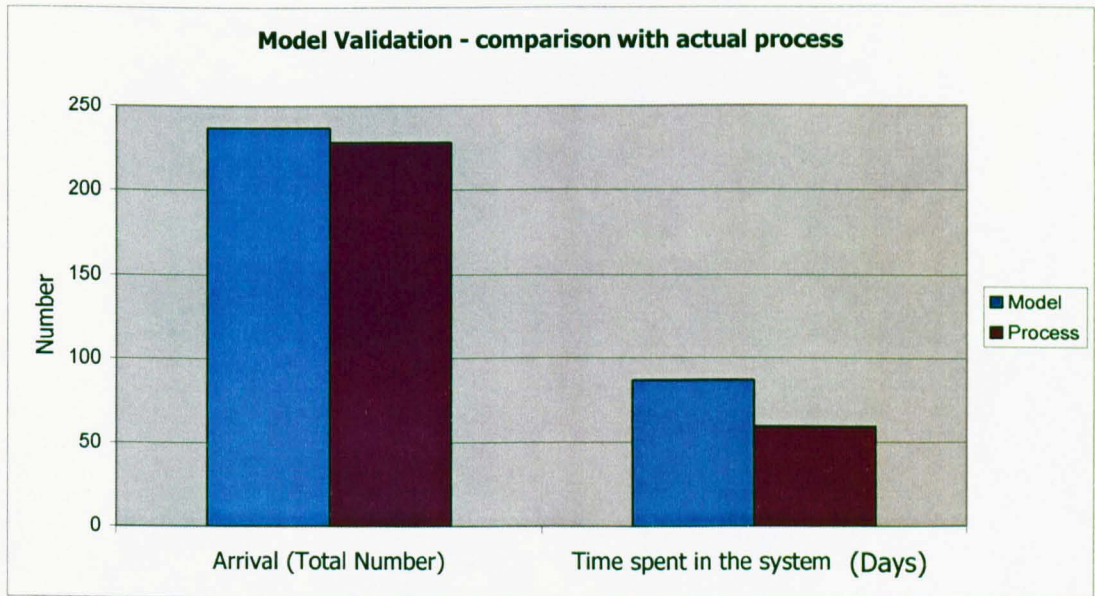


Figure 7.9 – Model results for validation

The results in the figure show that a representative system performance can be produced in the model, which was based on the same sets of role definitions (Resources) and Activities as the entropy and Q-analysis measurements. Arrival rates of 228 (actual) versus 237 (model) were

observed. Time spent in the system was longer, being 87 days for the model versus actual average figures of 59 days. This measured difference may appear to be significant, and can be attributed to the fact that the model treats ECNs in queues as First-In-First-Out (FIFO), which is a further simplification. The FIFO rule for the ECN is not strictly accurate, owing to priorities assigned to the ECN's versus the other work in the roles. Both the higher arrival rate and longer time spent in the system are conservative assumptions, and so any model changes will be based on similar conservative assumptions.

7.3.2 Modelling an intervention

It is clear from the results, both observed and simulated, that the ECN administrator is a bottleneck. The role is also very eccentric in the current process, being the least integrated (relative to its connectedness) into the structure. The principal change proposed is to integrate the work of the ESG CAD Engineer into the ECN Administrator role, and to create two cross-skilled queue servers in ECN Administration. This removes one queue between the two roles in ESG. This new cross-skilled role is being referred to a Change Control Engineer (CCE). This redefinition of Activities and Resources produces a new incidence matrix between Activities and Resources in the hierarchy. How the new role of CCE integrates into the structure is shown in figure 7.10.

	ECN Entry	Review at committee	Investigate implementation	Assign Actions	Complete Actions	Track Actions	Implement Change
CCE	1	1	0	1	1	1	1
Purchasing	0	0	1	0	1	0	1
Actionees	0	0	0	0	1	0	0
Committee	0	1	0	0	0	0	0

Figure 7.10 – Mapping relation for modified Resource set

Figures 7.11 and 7.12 show the resulting connected structure and eccentricities.

Q-Level	Participant
5	{CCE}
4	{CCE}
3	{CCE}
2	{CCE}, {Purchasing}
1	{CCE, Purchasing}
0	{All}

Figure 7.11 – Q-analysis for the revised relationship

Participant	CCE	Purchasing	Actionees	Committee
Eccentricity	2	0.5	0	0

Figure 7.12 – Eccentricity for the revised relationship

The implication of this change is that both Purchasing and CCE roles are more highly integrated into the structure with the other roles, and that the ECN administration (CCE) role is now more highly connected and participates in a key action, *i.e.* completion of drawing changes. This was then modelled, starting from the original Arena representation of the ECN process. The new process layout is as shown in figure 7.13.

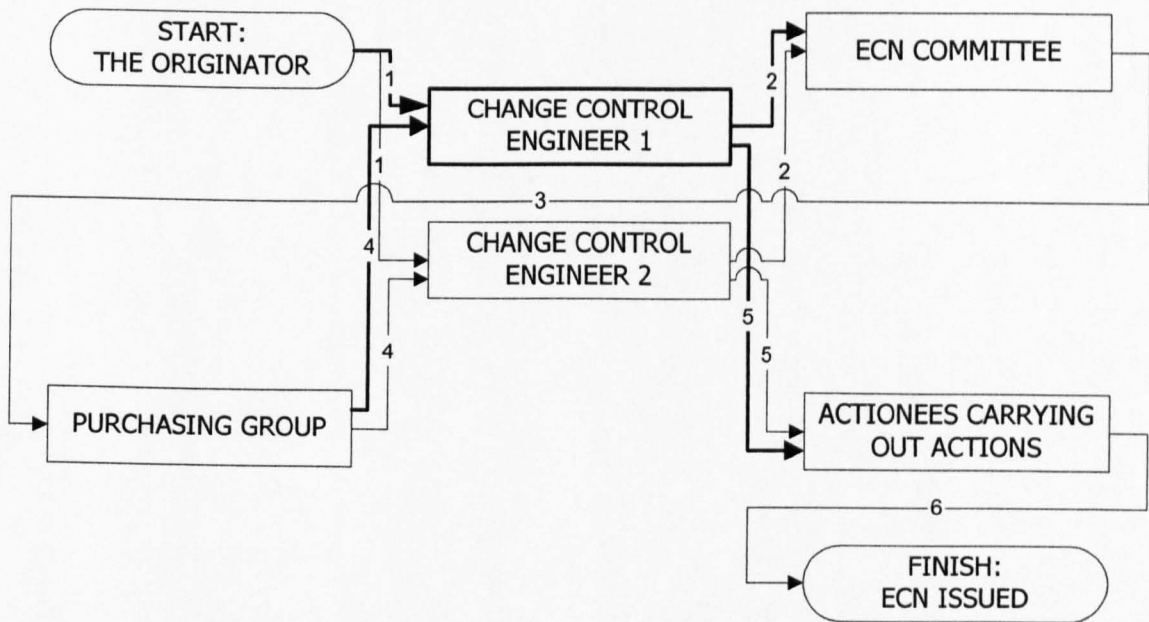


Figure 7.13 – Modified ESG roles and the creation of the CCE

This model shows two queue servers, working in parallel on ECN’s. This includes the CCE now carrying out the actions of making drawing package changes. The other change made in the model was that 25% of the ECN submissions (the approximate proportion of ECNs raised purely

to obtain part numbers for stock records) were automatically passed through the system via a fast track routing, reducing the spurious and redundant workload on the ESG. The model results show some changes to the performance of the process in figure 7.14.

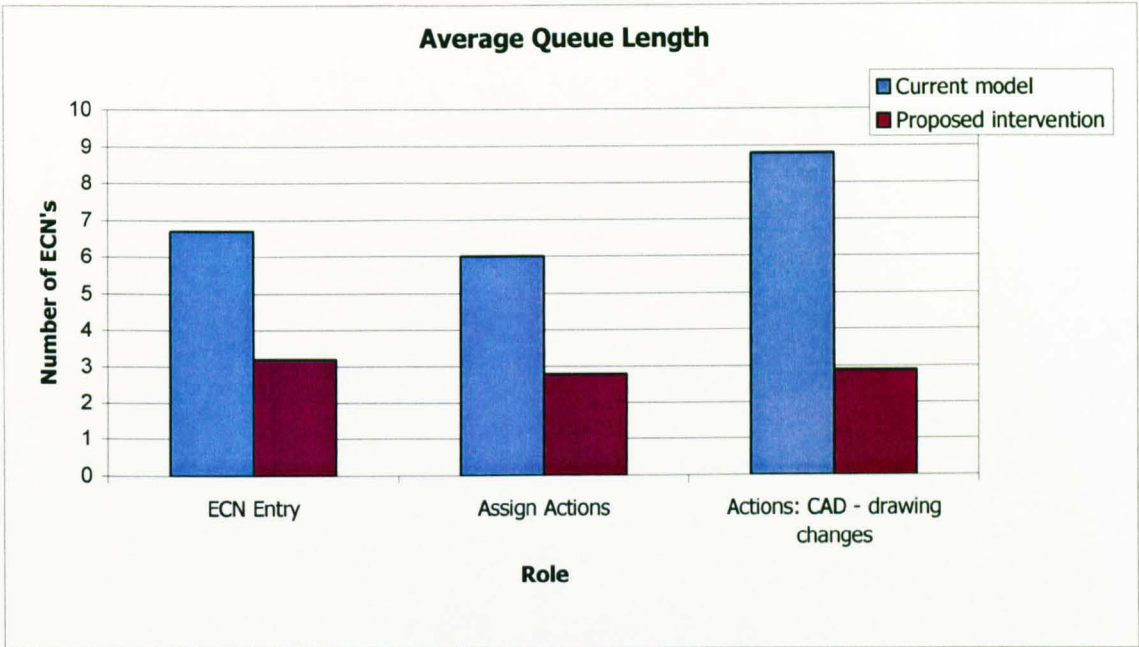


Figure 7.14 – Average queue lengths for Activities reported from Arena model

Theory predicts that two queue servers in parallel replacing a pair in series provide the same total capacity as they have more work to do per ECN, but that queuing times reduce. The model also indicates this by reporting the average queue length reducing by a factor of two.

These results remain removed from the actual process by the inappropriate use of the FIFO precedence rule in the model (see above). They do however show substantial reductions in queue lengths at the two resources in the ESG. Queue length reductions at each server will produce an immediate net reduction in ECN throughput times at these operations undertaken within ESG. Reduced queue dynamism indicates fewer states (*i.e.* less entropy predicted) and hence more predictable behaviour of the queue server.

Based on these predictions, the decision was taken to implement the proposal, and to create the new role of Change Control Engineer.

7.3.3 Implementation of intervention

The performance measure of ECN throughput time was implemented on the system. The data were available for all historical ECNs but had not been used as a measure. This was agreed by a subset of the stakeholders (to whom the study results were presented) as a good starting point. This would therefore be used as the single measure for improvement of the throughput capabilities of the process resulting from the intervention.

The same overall number of people (*i.e.* resources) was available in the ESG, but redeployed to perform both ECN Administration and CAD drawing changes. This required the additional resource allocation in computers to allow two people to perform CAD drawing changes concurrently. This equipment was already available within the organisation because of a rolling programme of capital equipment replacement that was creating a surplus of older equipment. A CAD software licence was also required, but this was also spare in the organisation when the changes were proposed. There was also a training requirement and whilst the ECN administration activities could be codified in procedures, proficient use of CAD software is a developed skill, and can take some time.

At the first implementation of the new job roles, it was not possible to also implement a “fast track” for ECNs that do not require committee review and actions (ostensibly those that are part number requests). Hence a higher workload than that proposed by the model was actually experienced by the ESG in their start-up. The changes were implemented from September onwards.

Eventually it was decided not to implement changes for the “fast track” ECN’s, and the system is still (at the time of writing) coping with the higher work loading.

The results of the intervention are shown in figure 7.15.

7.3.4 Actual results of the intervention

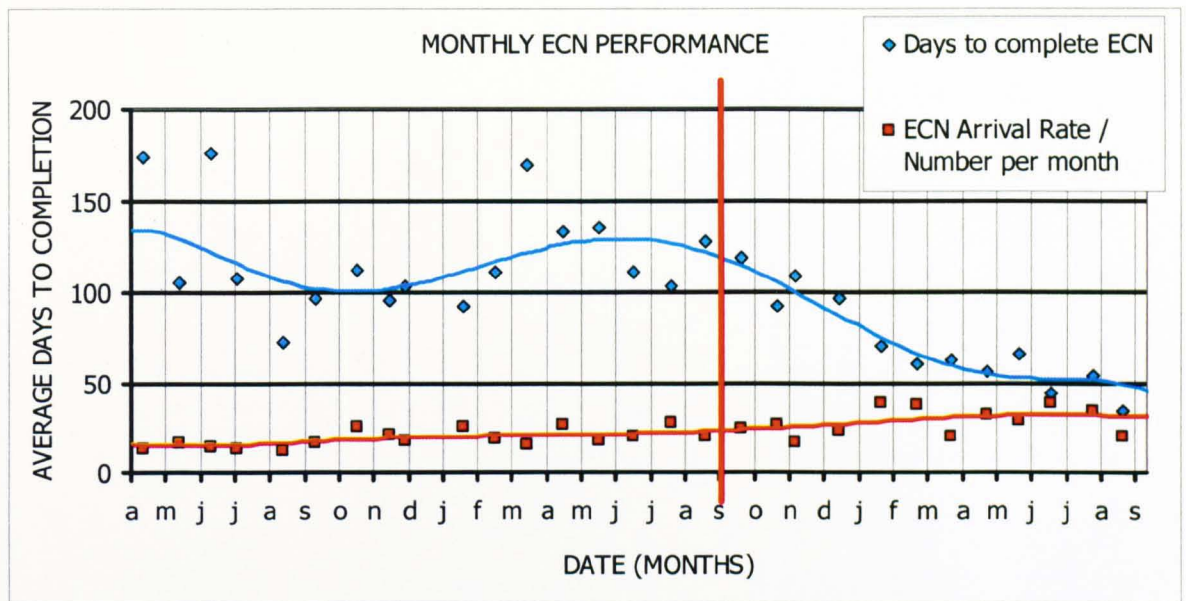


Figure 7.15 – ECN System performance improvement after September (vertical red line) implementation of modelled intervention

As indicated by the entropy measurements, the ECN Administrator was the principal obstacle to flow (bottleneck) and the intervention made to this role has had a demonstrable effect on throughput time.

This result shows a significant reduction in the throughput time of ECNs (top line), against a backdrop of a steady process loading, with a slight net increase in ECN arrivals (note the drift trend line up on the lower line). In statistical process control terms, it can be shown that a major process shift has taken place by the rule of thumb that there has been very close to a "run of seven" consecutive points below the existing mean of control limits (two of the seven are just above the mean). With only seventeen points available before the intervention, formal control limits have not been calculated (best practice dictates that twenty points are required).

As predicted by the model, queuing time has been approximately halved, as the mean throughput time has reduced from 120 to 54 days. The most recent seven measures had a mean value of elapsed 54 days throughput time. In the seventeen months prior to the mean and standard

deviation were 120 and 39 days respectively. Taking this as our population, and taking these final seven points as the sample, a significance test was performed. It is possible to conclude that a sample size of 7 with a mean of 54 is a significant result from a population of mean 120 and standard deviation 39, having a test statistic z value = 4.477.

This change in performance is without any major re-engineering of the actual mechanisms for the ECN, and any change to how other process participants outside of the Engineering Services Group are expected to work. This shows also that the ECN administration role was a bottleneck, and that by concentrating on relieving the bottleneck, that the flow characteristics of the entire system can be improved. Furthermore, the queue of the ESG CAD engineer has been eliminated completely.

The impression of the rest of the company is that the service level and performance from the two people working in ESG has improved greatly. ESG is still coping with "fast track" ECN's. This is possible because the throughput time is now so much shorter for all ECN's that it fits the activity cycle for the customers of this type of ECN.

7.4 Conclusions and discussion

7.4.1 The relationship between flow and the Activity-Resource relationship R_{AR}

This case study was concerned with the definition of specialist roles within a process, and how work in the activities of a process should be divided between functional groups and job roles. This differs from the previous study, which was focussed on sharing a range of skills between a pool of people who should be equally capable of acquiring the single skill defined in a standard operation.

The result of the entropy study was that the ECN Administration task was identified as a bottleneck, and that intervention based on redesign of this role (creation of the CCE) was able to alleviate this beyond recognition. ECN Administration was also identified as a highly connected

but highly also eccentric participant in the process. Perhaps counter-intuitively, further increasing the involvement of the bottleneck resource in the process has had the effect of reducing the obstacle to flow that they present.

A major queue has also been removed from the process by eliminating the ESG CAD engineer role completely, and also making it part of the role of Change Control Engineer. In doing so, it was possible to create a pair of CCE's, and this has relieved the bottleneck by redistributing the workload.

7.4.2 The effectiveness of joint measurement for process improvement and stakeholder issues

The approach of using the two complexity measures of entropy and Q-analysis to describe flow and structure respectively has proved moderately successful in this case study.

To return to the issues raised by the stakeholders during the interviews (see Appendix section B.1.3):

- *The process is slow and unwieldy.* This has been addressed by the redesign of the role of the ECN administrator and the ESG CAD Engineer to resource ESG with two CCE's. The result is that the throughput times have halved for ECN's. This reduction in lead times has relieved pressure on the departments who were previously having to carry on with their internal departmental processes "at risk" in lieu of an ECN being successfully approved and completed;
- *There is no visibility or feedback for originators or other participants.* This remains true insofar as the roles of and explicit communication to the non-CCE's in the process has not changed. However, it should be noted that the number of ECN's live in the process (effectively the work in progress) is now greatly reduced, and there are two people carrying out the administration tasks as required. This provides an improvement of a factor of four on the number of ECN's each administrator has to keep track of. The new role of the CCE has increased the connection of the ESG team to the rest of the resources

carrying out the process. This is realised by the CCE making any drawing changes as ECN actions, and so is able to organise their work to avoid activities getting “out of sequence”. This has had the effect of stopping the non-preferred practice of sending an ECN to the purchasing group for implementation without a complete drawing package being available to them;

- *The process is not being managed explicitly.* This has almost certainly changed for the better (the stakeholders agree with this), without any extra supervision, minimal training and infrastructure being provided. The expansion of the ESG roles (changing the structure of the activity-resource relation) to include stewardship of an ECN from start to finish has provided increased ownership from the ESG. The introduction of a performance measure has also helped considerably by injecting a perceived need for improved performance into the process. There is need for a caveat on this matter. The phenomenon of a Hawthorne effect when studying processes is possible, *i.e.* external attention devoted to the ESG for the duration of this study could be a possible explanation for the improvement produced by the people in the ESG. By way of mitigation of this, it is encouraging that improvement has continued after the explicit attention of the case study was discontinued. The results presented in figure 7.15 were obtained from the ESG some time after the overt spectacle of their role changes.

7.5 Implications for the research questions

Research Question 3

Once again it has been possible to identify the complex system agents of interest in the system under study, and construct an Entity-Activity-Resource framework. Entities are change notes, possessing both an information and material facet (each facet having different values and implications in the system). Activities are the steps in a generic process and the resources are the job descriptions that carry them out. Only in the case of the two full-time occupants of the system (ECN Administrator and CAD Engineer) does this imply a specific person in the same way

that an operator was implied in Chapter 6. A discrete event simulation model was constructed and able to show that similar to actual behaviour could be reproduced based on this framework.

Research Question 4

The study looked simultaneously at the information and material queues created by the flow of entities through the engineering change control process. This revealed that the set of queues of interest were in fact the information “waiting for action by...” rather than physical piles of change notes. A conventional process mapping technique such as value stream mapping would apply the same inventory counting techniques and only the material queues would have been observed. Also the sort of information sought (cycle time, number of operators, quality yield rate *etc.*) would not be available, necessarily relevant or helpful to understanding the process.

The R_{AR} relation showed that the greatest flow obstruction (when measuring the more meaningful information content of the change note entity) was also the most eccentric. This insight provided impetus for a counter-intuitive experiment on the discrete event simulation model. The insight of “operational effectiveness” would be that the ECN Administrator resource was a bottleneck, and should not be further loaded by a further expansion of their job description. A similar rethink of the CAD Engineer job description was undertaken (merging the two roles into that of Change Control Engineer). There was a marked flow improvement coinciding with the improved overall integration of the resources into the structure of shared activities. Further validating the model, this was reflected when an intervention was made in the actual system.

This notion of process management / ownership (itself an established “operational effectiveness” concept) may be seen to be an emergent property from the distribution of activities (visibility of queues *etc.*) in a set of stakeholder job descriptions. The survey of literature on Business Process Engineering did not reveal any such insight into what the physical embodiment of process ownership is or should be.

This study therefore shows three examples of novel insights from the use of the complexity measures on a complex framework representation of a manufacturing system.

Research Question 5

The model was successfully applied in a more loosely defined process environment. This produced insights that would not have been available using lean or other contemporary “operational effectiveness” tools.

Research Question 6

This case study was (like Chapter 6) highly operational but the nature of the intervention made did have more strategic (in this case human resources) implications. Examples of this include what sort of person (skill set and personal profile) to recruit into the Change Control Engineer role. The scalability of the original roles have also changed (both people employed can now do one another’s jobs), with implications for productivity improvements, risk from loss of “critical staff” in the future *etc.*

Research Question 7

“Absolute excellence” may again be shown to include the absence of flow obstructions in a process.

The leanness of the system in terms of resource provision is more difficult to gauge since most of the resources active in the process also do other work. Hence the IDLE or other state of the queue server resources was not considered in the context of this study. However, for the two full time people working in the process, a change in their work organisation (the EAR framework structure) produced a massive and sustained improvement to overall process performance. Whilst it was not possible to correlate or otherwise structural eccentricity to flow obstruction, it

can be concluded the new structure put in place gives more capacity for flow without adding more resources.

CHAPTER 8 - INK & SOLVENT DELIVERY BUSINESS

8.1 Experimental objectives

Chapters 6 and 7 have provided examples of the use of the complexity-based model on the actual processes of a manufacturing organisation; in one case a manufacturing operation and in the second case an office system. In both cases, the complexity-informed measures have been able to give insight into the systems under study that would have been unavailable from the use of conventional tools and measures.

This Chapter will look at a case study that possess both operational and strategic facets, and thus attempts to address Research Question 6. The objective of this study is to test the model and methodology under the set of conditions in Figure 8.1.

This chapter investigates a relatively simple system (in terms of numbers of agents) but has attempted to look at all of the relations simultaneously in the Entity-Activity-Resource (EAR) framework. The system is operating in what is believed to be a much more turbulent environment than previous studies, as demonstrated by greater (unknown) variety and unknown arrival pattern of orders.

The study also tests the definition of the EAR hierarchy with the use of a recursive subsystem, which is a physical sub-process for the manufacture and packaging of inks and solvents. Given this recursion, the nature of the entity also changes in so far as only a small part of the system sees the input/output order. The rest of the system and the subsystem are concerned with the provision and availability of the materials to be dispatched in the order. This study will therefore also test how well the framework supports a change of focus in the EAR framework in relation to the system it is describing.

The axes of this study (compared to proceeding chapters) are summarised in figure 8.1 (reproduced from Chapter 5):

Chapter	6	7	8
Brief synopsis	Single Piece Flow assembly of printers	Engineering Change Control	Ink and Solvent Delivery Business
Cover set hierarchy Relationship(s) of interest	R_{AR}	R_{AR}	R_{EA} and R_{AR}
Size of sets of interest (Number of agents)	Very Large	Small	Small
Anticipated complexity of considered relationships	Large	Small	Small
Nature of flow (materials, information, both)	Materials	Both	Both
Evidence of recursion of systems	None	None	Yes
Entity variety	None	Limited, known	Very Large

Figure 8.1 – Case study axes

Full details to the background of this case study, including the identification of stakeholder issues, hierarchical set membership; process mapping and subsequent aggregation are discussed in Appendix C, and shown in overview in figure 8.2.

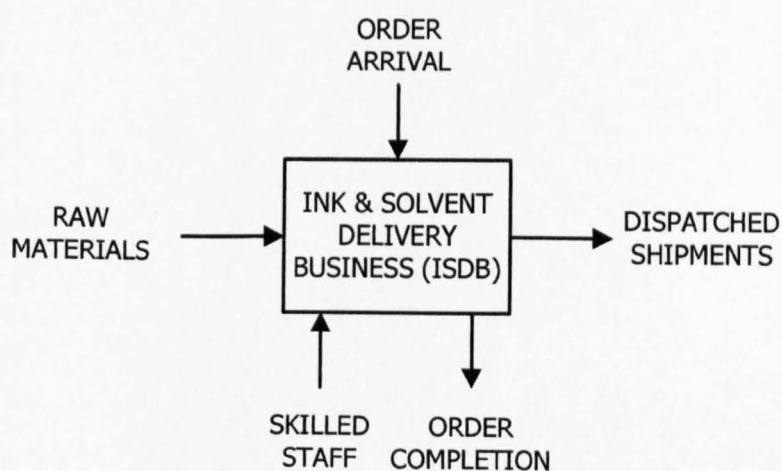


Figure 8.2 - IDEF₀ function block for the Ink and Solvent Delivery Business (ISDB)

The stakeholders are primarily interested in the current and future capacity of parts of the process and its impact on the manufacturing system response that may be offered to meet customer order requirements.

8.2 Study Results

A worked example for the case study in Chapter 7 is given in appendix B, in section B.3 for an entropy calculation and sections B.4.1 for Q-analysis and B.4.2 for Eccentricity calculation.

8.2.1 Entropy Study and Results

The entropy study was carried out over a period of six weeks in May and June 2004. Data was collected by Aurelien Bauplé, a placement student from IFMA (working under the supervision of the researcher). Seven activity queues were observed a total of three times per day (Monday-Thursday) and twice of Friday. This period included a Bank Holiday and so a total of ninety-five observations were made per queue in this period. Looking first at the observations of queues without consideration of server states, we see the flow obstructions in figure 8.3

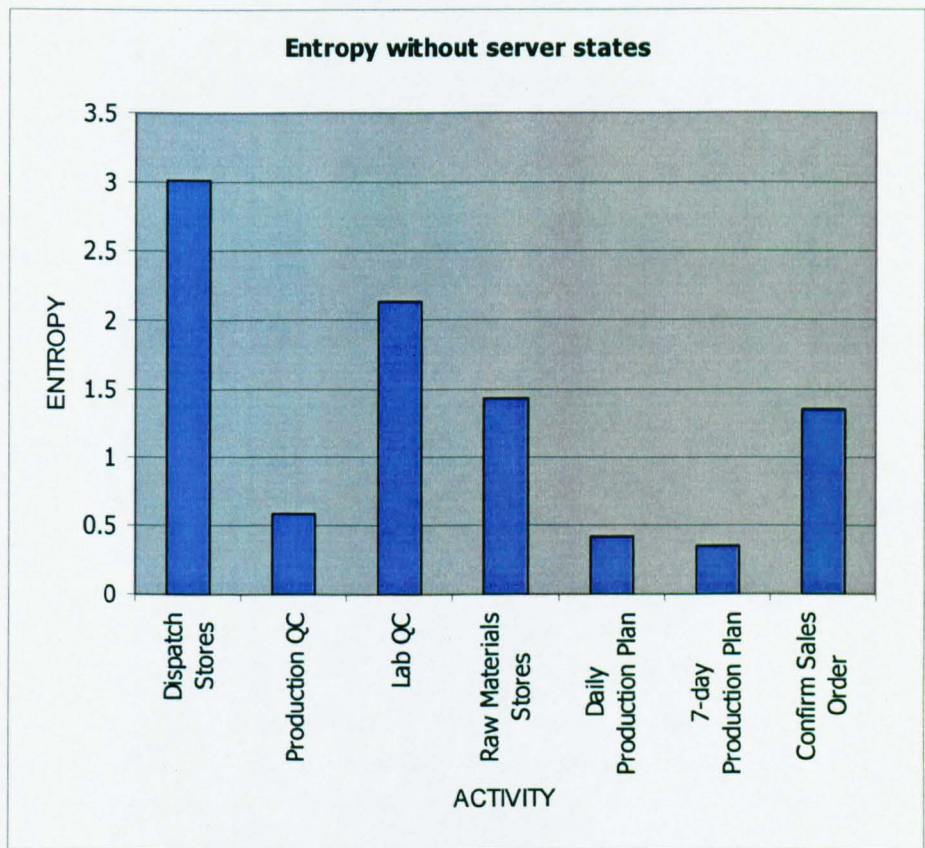


Figure 8.3 – Entropy Results without server states for queues

These results show that the greatest obstacle to flow in this process is being exhibited at the queue for: dispatch stores; the Lab QC (of raw materials); the raw materials stores (*i.e.* delivery performance of raw materials suppliers), and in the confirmation of sales orders.

The plant-based operations of complying to a seven day requirement for materials, achieving a daily plan and carrying out production QC on batches are all of a much lower entropy, indicating that they are not constituting a major obstacle to flow.

Having established which areas are of interest, the entropy-with-states measurements may usefully be reviewed. These are shown in figure 8.4.

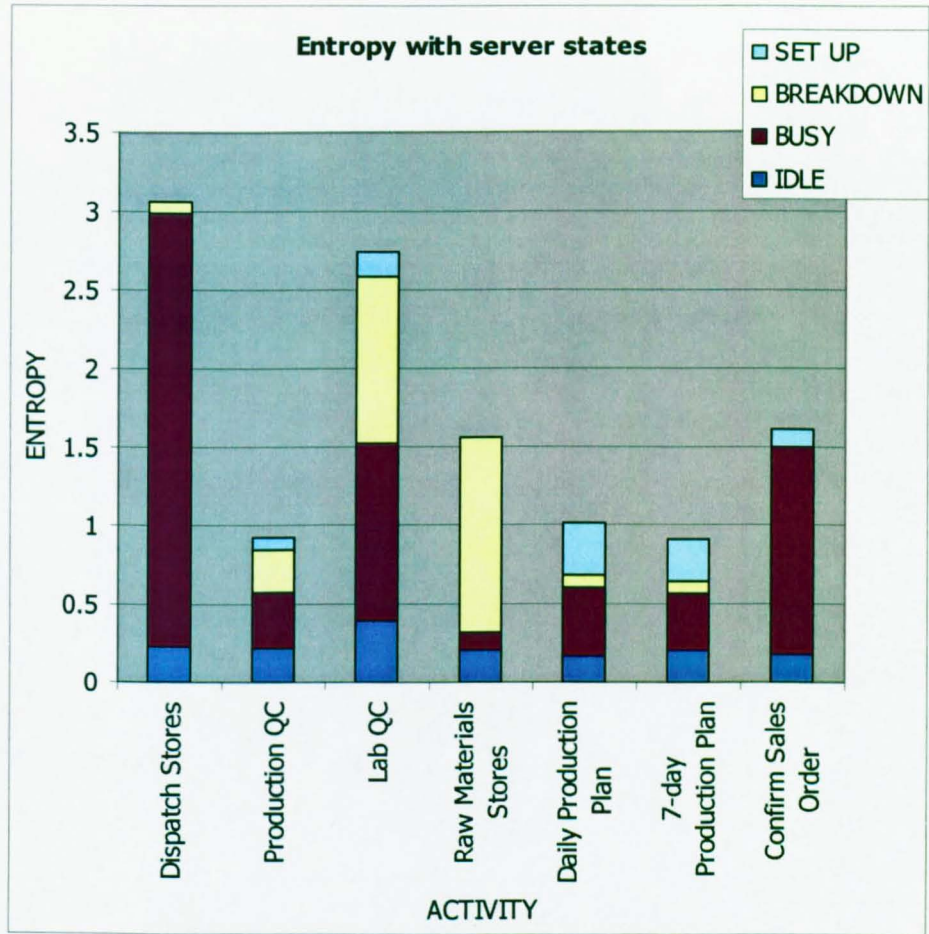


Figure 8.4 – Entropy with server states

The states of the queue servers reveal the nature of the disturbances that are causing the obstacles to flow in the Ink and Solvent Delivery Business process. The dispatch stores are

picking orders and are constantly busy. This sort of high entropy with a weighting towards BUSY states indicates that there is insufficient capacity in this activity to carry it out. The other explanations may have been that there

- is a huge amount of variation in the arrival pattern, leading to a “famine and feast” of work loading. This would also have produced a high flow obstruction from IDLE states;
- are a number of stoppages from personnel availability, equipment unreliability, stock shortages to meet orders, carrying out changeovers *etc.* This would have produced a high flow obstruction from BREAKDOWN or SETUP states.

The issue of available capacity was discussed with the ink manufacturing team, who found this result to be contradictory with their expectations. This is discussed further in the conclusions to this study. This activity is permanently manned, and it can be concluded that the cause of the obstacle must be the design of the task or the sheer work content of what this activity entails.

The confirmation of sales orders proved to have relatively high entropy, also dominated by the BUSY state. The order arrival pattern is a factor here, with the area being constantly highly loaded by other orders for printers and other spare parts. This is reflected by the occurrence of some SETUP and IDLE states. Given the sequence dependence of the Dispatch Stores on the confirmation of sales orders, it is of interest to note that the entropy increases with the flow the process, *i.e.* that these jobs are not functioning to attenuate disorder, but that they are transmitting and amplifying what manifests itself as flow obstruction at later activities. This would not be surprising if the OTIF (On Time In Full) performance of the system was poor; that is extremely good warrants some further investigation. This will be reviewed in the Q-analysis of the R_{AR} relationship.

The other pair of close-coupled processes with high entropies is the Raw Materials Stores and the Lab QC activities. There is substantial BREAKDOWN in both activities, indicating poor supplier delivery performance and responsiveness in carrying out Lab QC to verify that what has been delivered is to specification. There does not appear to be any substantial impact on the compliance to the Daily Production Plan, which has a tiny proportion of BREAKDOWN states

(mostly recorded as related to machine reliability). This is because the inventory practices are buffering the poor delivery performance of suppliers, principally because the order quantities of materials are relatively low in all scheduled deliveries, and Linx has relatively little leverage with its suppliers over order quantities and performance. This is exacerbated by the fact that most scheduled delivery items are type approved proprietary raw material formulations such as resins and dyestuffs.

The availability of materials is confirmed by the absence of any breakdown states attributed to materials shortages in the 7-day and Daily Production Plans.

One drawback in the current Lab QC activity is that materials failing their specifications are not rejected to suppliers for corrective action as fast as they could be. Inventory holding policy is also buffering the delays resulting from this. The BREAKDOWN state was observed to be attributable to the unavailability of a member of staff to perform the operation.

The similar but slightly higher entropy states in the Daily Production Plan than 7-day Production Plan compliance implies that the daily objectives are being met, with some variation over the course of the day. Hence the 7-day plan is being met but with minor variations on a daily basis as reviewed in the Daily Production Plan. These are concerned with the operation of the manufacturing activity. Aside from the BUSY states, there is a high proportion of SETUP and IDLE states. This, in conjunction with the overall low queue-only (without-states) entropy implies a surplus of capacity in manufacturing. The SET UP reflects that changeovers and the start of day are stopping the line, but that the planning of batches is allowing plenty of time for this. This may be validated against the incumbent conventional measures of how much time is "lost opportunities" and weekly litres output, against calculations of nameplate (nominal) line capacity. The estimate is that just over 50% of maximum theoretical capacity is being used (based on filling forty bottles per minute, the specification against which the line was purchased). The discussion of the implications of this for "operational effectiveness" is in section 9.2.

The Production QC shows similar entropic proportions of states as the Lab QC, but is greatly reduced. This implies that the same type of regime is being run in both sets of QC work, but that the queues are being managed somewhat more tightly in Production QC than Lab QC. This is because (as shown in figure C.3) Production QC results are required for the other manufacturing tasks to be possible. It is therefore more than likely that the Production QC contributes directly to the SETUP states in the Daily Production Plan compliance, and is a cause of lost opportunities in the plant. Whilst the production planning is tolerant of long start-ups and changeovers, this will not be a problem, but is reducing the effective capacity of the plant, and may warrant closer investigation if capacity becomes an issue.

8.2.2 Q-analysis of EAR hierarchy of cover sets

Q-analysis of R_{EA}

Upon inspection of the mapping relation between entities and the activities defined in Figure 8.6, it is possible to conclude that all entities undergo all activities in some form. A meaningful Q-analysis cannot be carried out that may be related directly to the allocation of the resources to the people who carry them out (R_{AR}). This part of the study was subject to an iteration of the methodology to address the latter stakeholder-posed questions at the strategic end of the spectrum. The implications of this for the total EAR framework proposition are discussed in a later section. However, it did raise the interesting issue that when Entities are defined in terms of their product composition, they do undergo different processing routes within the manufacturing sub-process described in Figure C.3. Looking at the relationship R_{AR} , though, will not provide an insight into the difference between these routes because the skill definition of manufacturing operations (see Figure C.3) is not sufficiently detailed. The manufacturing (plant-based) skills definitions do not actually need to differentiate between the destination of the product being worked on, *i.e.* between the "IM" or "I2" warehouses.

The R_{EA} study was therefore redefined to look more closely at the operations within the manufacturing area, and needs to be treated separately from the R_{AR} study, which seeks to

answer what now appears to be sufficiently different, though still highly relevant questions posed by the stakeholders.

This allows a closer investigation of the issue of plant utilisation and capacity raised in discussions with stakeholders. A Q-analysis was therefore carried out using the R_{EA} between the customer order Entities and the manufacturing activities carried out on them, using a new Activity set. This new relation is called R_{EA}^*

The implementation matrix for this is derived by evaluating the matrices for the composition of the Entities (expressed as seven meta-products) with the redefined Activities (based on one of three manufacturing routes in Figure C.3). This also changes the focus from the people holding skills as resources, to the physical equipment in use (Figure 8.5).

Meta-product \ Entity	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25	26	27	28	29	30
Vacuum solvent (VS)																													1	1
Third party Line Solvent (TLS)																												1	1	1
Third party Line Ink (TLI)			1	1		1	2	1			1	1	1	1	2						1	1	1	2	2	1				3
Bulk Solvent (BS)	1	1	1	1	2	2	2	2	3	3	3	3	3	3	3	4	4	4	4	4	4	4	4	4	4				2	4
Bulk Ink (BI)		1		1	1	1	2	1	1	2		1	2	3	1	1		2	3	4	1	2	3	1	2	1	1		1	1
Third part Vacuum Ink (TVI)														1	1	1							1	1	1			1	1	1
Speciality Ink (SI)								1								1														

Figure 8.5 – Revised incidence matrix for how much of each type of product (rows) appear in each order entity (columns).

The following implementation of products onto manufacturing routes exists, shown in figure 8.6:

Manufacturing Activity \ Metaproduct	VS	TLS	TLI	BS	BI	TVI	SI
Manual vacuum fill (1)	1	0	0	0	0	1	0
Direct fill on main line filler (2)	0	1	1	0	0	0	0
Mix, filter and fill on main line filler (3)	0	0	0	1	1	0	1

Figure 8.6 – Manufacturing routes for each Metaproduct.

This yields the following resulting matrix for the largest demand for a manufacturing route in figure 8.7:

Manufacturing Activity \ Entity	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25	26	27	28	29	30	
Manual vacuum fill (1)															1	1	1							1	1	1			1	1	1
Direct fill on main line filler (2)				1	1		1	2	3			1	1	1	1	2						1	1	1	2	2	1	1	1	1	3
Mix, filter and fill on main line filler (3)	1	1	1	1	1	2	2	2	2	3	3	3	3	3	3	3	4	4	4	4	4	4	4	4	4	4	1	1		2	4

Figure 8.7 – Product Matrix of the implementation matrix for R_{EA}^* , with variable (non binary) values indicating D value assigned (1-4 assignment refers to the size D value in section appendix C.2.2).

If this is sliced at a critical value ≥ 1 (*i.e.* all Entities represent a significant connection since an order cannot be shipped incomplete), the Q-analysis for the Activities in the matrix is in figure 8.8

Q-level	Activity
28	{3}
...	...
19	{2}, {3}
18	{2,3}
...	...
8	{1}, {2,3}
7	{1, 2, 3}

Figure 8.8 – Q-Analysis for revised Activity

The resulting R_{AR} matrix would include the key equipment used for each Activity (manufacturing route), and would be based on Figure C.3. This was not done because the operational differences between routes are simple enough to compare without a further Q-analysis at the lower level in the EAR hierarchy.

Figure 8.8 shows that when all product quantities are considered in an order ($D \text{ category} \geq 1$), a highly connected structure emerges. This indicates that to complete almost all order entities, almost all equipment in the manufacturing area has to be used. The lower Q-level of the {1} activity shows that the vacuum filling activity is the least connected, and is connected to the other equipment by only a Q-level of 7. As indicated in figure C.3, this means that the vessels, filters and main line filler are required for 29 out of the 30 most important order Entities. All thirty entities require the main line filler in some form. The importance of this piece of equipment indicates that there is no redundancy in the processing routes for products and that it is very highly used to produce order entities.

Whilst this does not relate directly to the capacity loading on these resources in absolute terms (there are more effective and direct ways of doing this), it provides an alternative measure of how the structure would change if for example it became possible to route Third Party Line Ink or Solvent via vacuum filling instead of the main line filler. If this was done, activity {2} would then

use the vacuum filling equipment, and the Q-level of the vacuum equipment (*i.e.* the significance of it in the Entity structure) would jump from 8 to 19. Similarly, the relative eccentricity of the other equipment used would decrease.

Q-analysis of R_{AR}

Despite the changes to the Entity-Activity relation defined above, the R_{AR} relation was left unchanged to provide some continuity to the case study/

The implementation matrix for the relation R_{AR} is shown below in figure 8.9.

		ACTIVITY								
		Confirm Sales Orders	7-day Production plan	Raw Materials Stores	Lab QC	Mixing	Automated Production (App)	Production QC	End Of Line (EOL)	Dispatch Stores
		1	2	3	4	5	6	7	8	9
RESOURCE (Person)	1		1			1	1	1	1	1
	2		1			1	1	1	1	1
	3					1	1		1	1
	4				1				1	
	5					1	1	1	1	1
	6						1		1	
	7						1		1	
	8			1						1
	9									1
	10						1		1	
	11	1								

Figure 8.9 - Implementation matrix for R_{AR}

The Q-analysis for both Activities and Resources are shown in figures 8.10 and 8.11. Turning to the dimensions of the set members, their simplicial structure and relative connections of the activities to one another, we see immediately that there is the very early emergence of a highly connected set of skills (6 - Automated Production Processes and 8 – End Of Line, sharing fewer operators with 5 – Mixing and 9 – Dispatch Stores). There is also a total disconnection of the sales order-processing group from the rest of the process.

Q-level	Activity set members
7	{8}
6	{6,8}
5	{6,8}, {9}
4	{6,8}, {9}
3	{5,6,8,9}
2	{5,6,7,8,9}
1	{2,5,6,7,8,9}
0	{1}, {2,3,4,5,6,7,8,9}

Activity		<i>Q-top</i>	<i>Q-bottom</i>	Ecc
1	Confirm Sales Orders	1	n/a	∞
2	7-day Production Plan	1	1	0
3	Raw Materials Stores	0	0	0
4	Lab QC	0	0	0
5	Mixing	3	3	0
6	Automated Production Processes (APP)	6	6	0
7	Production QC	2	2	0
8	End of Line (EOL)	7	6	0.142857
9	Dispatch Stores	5	3	0.5

Figure 8.10 – Simplicial structure and Eccentricity of Activities in R_{AR}

Q-level	Resource set members
5	{1,2}
4	{1,2,5}
3	{1,2,3,5}
2	{1,2,3,5}
1	{1,2,3,5,6,7,10}, {4}, {8}
0	{1,2,3,4,5,6,7,8,9,10}, {11}

Resource (Person)	Q-top	Q-bottom	Ecc
1	5	5	0
2	5	5	0
3	3	3	0
4	1	0	1
5	4	4	0
6	1	1	0
7	1	1	0
8	1	0	1
9	0	0	0
10	1	1	0
11	0	n/a	∞

Figure 8.11 – Simplicial structure and Eccentricity of Resources (people) in R_{AR}

The most obvious result from figures 8.10 and 8.11 are the complete disconnection of the sales order-processing group (Resource 11) in the study from the rest of the structure. This is shown

simultaneously by both infinite eccentricity value and the fact that it does not join a structure with any other set member at the lowest Q-level dimension.

The remainder of the Resource set are part of a single simplex, with a common core of skills based in the production area (see above). Aside from the numbers of people required to man all of the workstations, this also supports the finding that the manufacturing of ink and solvent (actively using skills of mixing, APP, EOL) is a relatively well-supported activity within the team. The most skilled (highly connected) people all have this core to some extent, and this gives rise to the structure from Q-levels 5 to 1. Whilst this can be seen from an inspection of the incidence matrix, the relative impact of this can now be measured. Also, this is a relatively simple case study, and on a more complex system with more skills or people in the study, this may not be as easy to divine.

What also emerges at this level is that there are team members who are not well connected or especially well integrated. Person 4 and Person 8 both possess a skill that they share with others, plus a skill that only they possess. For Person 8 it is Raw Materials Stores and for Person 4, this is Lab QC, (activity/skill 3 and 4 respectively in Figure 8.7). The delivery performance of suppliers has been identified as the obstacle to process flow in the Raw Materials Stores. Unavailability of the operator is the cause of BREAKDOWN states in the Lab QC flow obstacle (shown in section 8.2.1 to be a high entropy value). This activity has a low dimension for both Q-top (1) and Q-bottom (0) because only one member of staff can perform this activity which, it also transpires, is not well integrated into the structural geometry of the relation (Person 4 has a Eccentricity value of 1 in a structure that is highly integrated). This goes towards explaining the BREAKDOWN states and poor synchronisation of this central activity within manufacturing.

8.2.3 Comparison of Entropy and Q-analysis measures for the R_{AR} relation

A correlation statistic for the Entropy and Eccentricity was calculated with the CONFIRM SALES ORDER removed from the data because the value of the eccentricity was infinite. The remaining data had a positive correlation value $r = 0.66$ between the queue-only entropy and the

eccentricity for each activity. A t-test for this set yields a test statistic value of 1.76. The 95% $t_{2.5, 5} = 2.776$ for this data set of 6 points. This is not a statistically significant result at this level. However, in addition to this, it is possible to make the following observations:

- There appears to be supporting evidence that high levels of connection and integration support a robust core set of manufacturing activities 5,6,8 for the present level of demands being placed upon the ISDB process;
- The poor performance of the Lab QC activity is also indicated by the poor level of connection (just one operator) and poor level of integration that this individual has. To all intents and purpose, he is a sole specialist;
- The poor flow properties of the dispatch stores activity is not reflected in the high degree of connection and relative integration of either the skill or the people possessing it. This might shed some light on the limitation of applicability, caveats for use and potential need for refinement of this joint measurement approach.

8.3 Modelling the delivery performance of the ISDB process

Given the changes to the Entity-Activity Relation (R_{EA}^*), the scope for the model was changed from representing the entire EAR framework as originally proposed. Chapters 6 and 7 demonstrate successful modelling to test the R_{AR} relation and so this was not sought again in this case, and modelling was not carried out in this case study.

Having elected not to carry out this step, conclusions for the stakeholder issues and hence rease questions of the thesis can then be drawn.

8.4 Conclusions and Discussion

8.4.1 The link between process flow and the Activity-Resource relation R_{AR}

The case study has further proven the link between the flow performance of a system and the structure of the relation by which resources are provided to execute the defined activities of the

process. More so than in previous case studies, the limitations of this technique have also been highlighted, and serve as illustrations of how to make best use of the joint measurement technique. This is illustrated by the following examples from the case study:

Dispatch Stores activity

The entropy measurement clearly shows that it is a bottleneck, and that the operators working there are constantly occupied by the role. Idle time and enforced stoppages are few and far between. Simply put, there would appear to be too much work for the available resource set. Staff carrying out the activity also cite the batching of orders for picking by the sales order processing group, but there was little evidence that this is a problem over and above the total amount of work being carried out at this activity. It is, however, entirely possible that IDLE states could be missed by the pattern of observation of the queue servers. Staff were reluctant to point to any IDLE time on their working day.

The bottleneck is highlighted by the structure of the relational mapping R_{AR} . The Dispatch Stores activity (skill) is held by many members of staff, and so there should be no shortage of people available to carry the activity out. It has a *Q-top* value of 5. It is only by considering its relative eccentricity (Ecc value = 0.5) to the rest of the structure that a real insight can be gained. This shows that the dispatch stores is a relatively separate skill set from the rest of the process. An investigation into the operation of this activity revealed that operator 9, who does not possess any other skills in the process, primarily carried it out, further exaggerating the separation of this activity from the rest of the team.

The absence of staff rotation through this activity (given that it is already disposed to be somewhat eccentric to the rest of the process) shows that even a highly connected activity can be ill understood and poorly supported by a set of available resources. When presented with these results, the team (led by Mr A) were surprised by them. The net outcome of this result, *i.e.* a bottleneck to flow and not enough slack in the activity to allow for rescheduling was being felt by Mr C in the shipping department. If staff are trained and capable but not rotated through

activities, then the Q-analysis of relational mapping will not provide a clue to the potential underlying root cause of poor performance.

Confirm Sales Order activity

Entropy measurement shows that this department is relatively highly loaded and contributes towards flow obstruction in the ISDB process. This activity is completely disconnected from the rest of the structure (or more precisely, this activity is not in the structure at all !). This group deals with the variation in incoming orders, but it appears that by batching up orders, they are also transmitting the disruption to the dispatch stores activity, which is already highly loaded.

This disruption is mitigated in other areas by the fact that the 7-day production planning activity and MRP run (and its associated purchasing) use the total order requirement and have visibility of it as soon as the order is confirmed. The creation of two channels for different types of order ("I2" and "IM" electronic warehouses) had gone some way to attenuating the disruption of order arrival and handling by sales order processing group.

Some cross-skilling between the areas of sales order confirmation and dispatch stores activity may help develop a better mutual understanding of the impact of individuals' work on their colleagues. This would modify the structure of the R_{AR} relation by including the sales order processing group, albeit at a low Q-level, into the complex.

Plant operation activities (Daily/7-day production plan, Lab QC, Production QC)

The low levels of flow obstruction caused by the physical ink and solvent manufacturing processes are attributable to the excess of capacity available in the manufacturing operations, and the sharing of the manufacturing skills amongst the core of the team. This latter point is witnessed by the large single simplex created around the core skills. Skills peripheral to the manufacturing activities are less well connected and integrated. It is the Lab QC and Production QC that require some greater connection and integration into the structure through further training of the staff to have the skill.

In the 7-day and daily plan compliance the creation of a queue arises when the plan is not achieved (through the real time observations) and arrears are created. Given that there are IDLE states, this implies that there are periods of time when there is no batch planned, and that there is excess capacity.

The excess of capacity in fact masks a reasonably significant proportion of states of SETUP and to a far lesser extent, BREAKDOWN. The SETUP pertains to the start of production in the morning (the plant is a single shift operation) and lost time between batches when changeovers are carried out. Given that the formation of queues is caused in this activity by lateness in the daily production plan, then the unpredictable and lengthy nature of SETUP can be shown by its contribution to flow obstruction by the queues it creates. Attempts to reduce flow obstruction and add capacity to the process would need to address both the repeatability and the duration of the SETUP activities.

8.4.2 The effectiveness of joint measurement for process improvement and stakeholder issues

The issues raised by stakeholders at the start of this case study were as follows:

- *A requirement for a better measure than litres output from the manufacturing sub process as a measures of reassurance that stock is available and that the plant is running properly;*

Entropy is has been shown again to be an excellent operational measure. If an automatic sampling regime can be implemented, then it may be possible to have real-time access to the entropy of queues with and without states for a rolling interval, indicating both the extent that activities are obstacles to flow, and the reasons.

This measure would actually synthesise some of the other, lower level operational measures used by the team into a single one that would give a measure of confidence that the process is "under control". This measure included supply chain delivery performance, plant efficiency, and overall

flow performance for all activities in the process. It can be used in isolation or more powerfully, in conjunction with the OTIF outcome measure of performance.

- *A review of the degree and dispersion of skills within the team;*

Q-analysis provides a way to look at the dispersion of skills and has again provided examples of poor flow that can be attributed to poor connection and integration of an activity into a process. When poor structure is causing the poor flow, q-analysis complements entropy measurement. This review has shown that there are skill areas that are not well integrated into the structure, and that they are the causes of disruption to successful flow in the instance of the ISDB process. A recommendation from the study must be to extend the integration of Lab QC (4) and Production QC (7) into the manufacturing team structure. Efforts may also be taken to increase the specific connection of the activities of sales order confirmation (1) and of dispatch stores (9) by cross skilling and job rotation. If these were done and the Q-analysis repeated, then the Lab QC (4) and Production QC (7) would appear in simplices at a higher Q-level. Confirm Sales Orders (1) and Dispatch Stores (9) would appear together in a simplex (represented by {1, ..., 9} at a Q-level determined by how many people are cross-skilled).

A caveat must be applied to the use of this measure, dependant upon both the definition of the activity/skill and the operation/supervision of the process. The example is the Dispatch Stores (9). It is a well connected (Q-top value of 5) and reasonably well-integrated activity (Q-bottom value of 3), yet it is not well understood by the team, and the fact that it is a capacity bottleneck surprised the team when this study was presented to them. This would appear to validate the "external" view of the process customer *i.e.* Mr C in the shipping department. The mitigation offered by the other team members holding the skill is that whilst they admit that they have not worked there recently (an admission in itself!), they agreed that there is a "right way" to carry out the activity. Working this "right way" enables the operator to complete the tasks more rapidly by carrying out the duties in particular sequences. This best practice (if it can be validated) is simply not codified in the process documentation at this stage.

The importance of maintaining a particular pace of working was also cited as a way to “keep up” when carrying out this activity.

Q-analysis will not deliver insights related to the quantity of work in a skill and how it is done by each operator, however it does help initiate a discussion into the actual reasons for shortcomings in an activity. Use of Q-analysis relies upon effective definitions. The activities clearly have shortcomings here (unlike in chapter 6) that the pace of work and optimal sequence are not conveyed or maintained in the execution of operations. This deviation from the concept of a standard operation (and hence from leanness) is an improvement opportunity. The “ILUD” concept discussed in section 2.3.2 develops a spectrum of qualification in a skill area, and may be of use in this area.

- *An investigation into flexibility and responsiveness of the dispatch picking of finished goods;*

The entropy measure has revealed that this activity is the biggest single bottleneck in the process, and that it is almost entirely a capacity overload (rather than being the result of external disruption, such as a supplier or conflicting requirement for the operator). There is no “slack” in the system to tolerate late schedule changes, and this would explain the sort of issues raised by shipping (who did not feature in the study as a resource, but is the immediate customer of the process).

- *A wish to understand current and future likely capacity (including a potential pilot line facility) as part of the strategy making process.*

Current Capacity

There is currently no capacity shortage in the manufacturing operations, indicated by low obstacles to flow in daily and 7-day plan achievement, high availability of stock for picking (no BREAKDOWN states attributed to this). To add capacity of cope with small increases in customer

demand, there is evidence that a programme of changeover and set-up time (SETUP state) reduction would be the first place to put improvement efforts. Cross training in Production QC (7) and in Lab QC (4) will reduce any further disruption of the manufacturing process.

More significant obstructions to flow come from Dispatch Stores (9), Sales Order Confirmation (1) and the Raw Materials Store (3) *i.e.* supplier performance. Dispatch Stores has been discussed in section 8.4.1. A greater understanding and communication of the standard operation in this activity (following lean principles) will assist flow improvement (reducing non-value added content in line with best practice) before additional capacity is necessarily added to this area. Next, Sales Order Confirmation is carried out as a batching activity and this could be investigated for exploitation using flow principles. This is a lower priority than the alleviation of the bottleneck downstream in the Dispatch Stores. Finally, raw materials stock levels are buffering the poor delivery performance of suppliers. The assumption that this state of affairs cannot be altered should be challenged, but is not a priority for the ISDB process at present.

The confidence held by senior management in the current and hence future capacity is attributable to the impression of an inflexible (overworked) dispatch stores. They probably also remember a history of artificially high short-term plant loading and apparent stock shortages that existed before the "IM" and "I2" warehouses were split, when stock was prematurely allocated to orders. Given that ink and solvent sales volumes have grown, it must remain a temptation to assume that there is still a pressing capacity shortage in the area. This study has shown that no capacity shortage presently exists, and that inflexibility of the process in the dispatch stores can be addressed by better skill definition and dissemination amongst the people doing this activity.

Future Capacity

The first attempt to gain insight into the provision of a process (with its activities carried out by resources) was not helped by the set definitions in the R_{EA} relation. To give more useful insights for the summary of customer requirements given by the Entity set of orders, the process was redefined by another relation, R_{EA}^* .

Based on Q-analysis of the R_{EA}^* relation, introduction of a pilot plant or other capacity additions will change the structural relation between the Entity orders and the way that they are produced by Activities consuming resources. This will not allow an exact capacity figure to be derived, but it will give some indication of the risk of the current manufacturing system and changes from new projects, particularly which Entities will be affected. The example given was for moving more types of meta-product (TLS, TLI) onto the Activity {1}, using manual vacuum filling.

An improved indication of capacity size could be gained by using the slicing indices on the incidence matrix. It must be remembered, however, that the capability must be retained to make all of the contents of all Entities, since a partial order cannot be shipped incomplete.

The creation of a pilot plant would allow speciality ink products to be made on a separate, small mixing and filtration line, requiring filling on the manual vacuum filler. This will change the intermediate implementation matrix used in Figures 8.5 and 8.6 to derive the final EA incidence matrix, which also changes. The change in the structure of the EA relation from moving the SI meta-product into activity {1} from {3} will make only marginal changes to Q-structure, and hence the operational risk of using that equipment. The management team are therefore shown that the increase in capacity and other benefits from pilot line addition may outweigh the slight increase in connection of the manual filling operations within the structure.

The current very high level of physical pipe work coupling of the mixing, filtration and automated filling line (figure 8.6 item [3]) and its q-analysis connection to just the automated filler (item [2] in figure 8.6) do identify that there is high reliance on just one suite of equipment. Without duplication of equipment (there was none in evidence), this is obviously higher risk. Decision-making could therefore benefit from the risk-based view provided by the measure. This would be by adding capacity to reduce the reliance of one suite of equipment in such a way that fewer Entities are connected to any one Activity, using any one set of equipment. This might lead to the decision to establish a second line rather than to speed up the existing automated line. However, the dominance of the bulk solvents (BS) and inks (BI) in the Entity set (figure 8.7) will

render it quite difficult to seriously reduce the risk without duplicating a capability to make these products.

8.4.3 The application of the EAR hierarchy

This case study has shown that it is possible to gain a useful insight from each of the relations R_{EA}^* and R_{AR} in conjunction with an indication of the nature of flow in the process. However, as a single, completely consistent framework, this case study has failed to show that a complete system can be used without some modification. The reason for this is that the rich relations that we wish to study will depend upon the causes of richness of the system itself, *i.e.* that the issues and drivers for complex behaviour in processes. Very different types of stakeholder issues were identified, affecting the critical definitions of set memberships.

It would have been entirely possible to carry out the Q-analysis on the original relation R_{EA} , but as discussed, it was not a rich relationship with any structure *per se*. On this basis the study was modified, expanding the manufacturing stages used in the model and including the equipment. The absence of a rich structure in the original R_{EA} relation still contains some value to the study, namely that the set definition as is does not contain the drivers of complexity (at that level of aggregation at least), and that the researcher must look elsewhere. This is in contrast with the successful insight gained into the system from the use of the set definition in the R_{AR} relation (see below).

A single EAR framework is useful only as long as the set of complexity drivers are themselves consistent, *i.e.* both the relationships are meaningful as drivers of systems complexity from the perspective of the stakeholders' issues.

8.4.4 Insight gained from a study of the Entity-Activity relation R_{EA}^*

The Q-analysis of the R_{EA}^* relation has revealed some interesting results:

- It has given some indication of how dependant the Entities are on the Activities (with the resources requirements implied). The high connection of the Activities shows that there is also a definite reliance on all of the equipment used in the activities. This is further compounded when it is considered that Activity {2} uses a subset of the equipment required for Activity {3}, as shown by a similar routing in Figure 8.4. This implies that a one-size fits all approach has been adopted to the manufacture of inks and solvents with the exception of a very few meta-products using Activity {1};
- The dominance of the use of main filling line for all Entity orders (regardless of their size or lead time) shows how heavily dependant the operational policy is on using inventory to make the lean-agile split which has proven so beneficial in the creation of the "I2" and "IM" warehouses;
- The more limited use of the Activity {1} vacuum filling (Q-level *q-top* of 8, integrated into the structure *q-bottom* of 7, relative eccentricity= 0.125) shows that even small volumes of products can connect to the structure through a large number of Entities, and can have a major influence on the ability of the company to achieve high levels in its On Time In Full (OTIF) performance.
- The Q-analysis of manufacturing resources in this way can therefore give an indication of the exposure to risk from reliance on one or more key activities and the resources that they consume (the new R_{AR}^* relation was not studied in depth because this is a relatively simple example).

The failure of the initial relation R_{EA} to show any novel structure is also an indication that for the Entity set thus defined, there is a common route through the high level process (Figure C.4) and relatively common routing for the more detailed physical manufacturing steps (Figure C.3). The only difference is the physical trigger for an allocation of stock. These two are not picked up by the Q-analysis (this is perhaps a deficiency in the measure), and so this view of the process reveals that the system is broadly the same for long lead, large quantity and short lead, small quantity orders. Insofar as this is a non-result (leading to a redefinition of the R_{EA} relation), it does show that the ISDB process is not established explicitly as a pair of lean and agile processes depending on the product made or customer served.

8.5 Implications for the research questions

Research Question 3

It was possible to identify the set of agents of interest for each of the Entity, Activity and Resources, making an EAR framework. However, (defining the operational and strategic placement of this case study), it was not possible to answer the range of stakeholder issues using a single, consistent EAR framework across both mapping relations R_{AR} and R_{EA} . A revised R_{EA} was defined (called R_{EA}^*) and the case study was able to continue, though to two sets of conclusions discussed earlier. This points to a potential shortcoming of the complexity-informed model presented in this thesis, namely its reliance upon the quality of the EAR set definitions made early on in the methodology cycle.

Research Question 4

This chapter has provided situations for the richest use of the measures of patterns of complex structure and behaviour to be made. As with chapters 6 and 7, it will be argued that the two complexity-informed measures have provided insight over and above that which have been obtained from the use of conventional "operational effectiveness" measures and tools.

The use of a visual management board in conjunction with a one-off value stream map would have produced the same confusing results in the Dispatch stores as the complexity measures showed. In both cases, it was necessary to dig deeper to understand why the one operator had a different experience of carrying out a standard operation compared to his peers. Because the lean tools are self referential (*i.e.* value stream mapping assumes standard work operations are in place as building blocks of the process), they can suffer the same problems as an ill defined set in the EAR framework. In this respect, the new complexity informed measures fare no better than lean tools. However, the flow obstruction measurement made in Entropy terms was faster to pinpoint the likely cause of the issue, because it was able to eliminate upstream activities as

potential causes of flow disruption. This then allowed the focus for investigation to be “so just how standard is our standard work operation in the dispatch stores?”, and do so legitimately with data *i.e.* because there was confidence that disruption was not being propagated elsewhere. This numerical result for flow obstruction is a property of this measure of complexity. It allows fact-based decision-making. This is a benefit that the “operational effectiveness” worldview encourages but would not have an explicit tool to offer in this case. Hence this is a further example of the improved insight from the use of complexity in manufacturing systems.

Research Question 5

The complexity-informed model has been applied with less success in the instance of this chapter compared to chapters 6 and 7, but therein it has highlighted several areas of interest. In addition to providing another example of how this model provides additional benefits over “operational effectiveness”, its shortcoming has also been of interest.

In particular, this pertains to the importance of accurate set definition for the EAR framework of the system under study, the example discussed at length being the nature of the standard work operations being taken as the building block of the process. The other illustration of this comes from the fact that the same EAR framework was insufficient to address both operational and strategic issues in the same case study.

Research Question 6

This chapter has shown that the complexity-influenced model presented here has had limited success in its first use on a strategic rather than purely operational problem. However, it is worth pointing out that this failure can also be observed with “operational effectiveness” tools and techniques. This has been noted in the strategic literature that for a long time competitive strategy literature relegated “operational effectiveness” to the pursuit of “best practice”, a competitive zero-sum game that may lead to loss of distinctiveness *etc.*

However, there are areas of success in the use of the complexity-influenced measures for strategic issues, especially in exposure to operational risk. Whilst not explicitly researched in the “operational effectiveness” literature study made in Chapter 2, there is no obvious way in which a similar exposure to risk could be obtained from the tools of “operational effectiveness”. The only tool that could be applied to this decision problem would be the method by which lean manufacturing cells are designed by clustering the process requirements of like products.

Research Question 7

Once again, one aspect of “absolute excellence” is given by the complexity-based measure of flow obstruction. The use of the other complexity-informed measure of structural relationships between sets in the defined Entity Activity Resource framework appears to be somewhat context specific. The indication is that this returns to the research question previously posed by earlier research into the dimensions of flexibility, which will be discussed in the conclusion in chapter 9.

CHAPTER 9 - CONCLUSIONS AND FURTHER WORK

9.1 Introduction

This research has shown that the null hypothesis (that no new insights are available complexity science measurement of manufacturing companies) can be disproved in support of the thesis proposed in Chapter 1. This has been done by

- A literature survey of the current state of the art in the description and measurement of “operational effectiveness” and complexity science for signs of linkages between the two fields. Little linkage was found, being restricted to pockets of interdisciplinary research (Chapters 2 and 3);
- The identification of a novel framework for the description of a complex manufacturing system in the form of interrelated sets of Entities, Activities and Resource agents. The further identification of a pair of measures for patterns of complex system behaviour and structure, and their validation for usefulness in the context of the recognizable terminology of “operational effectiveness”. Moreover, defining the resources as agents demonstrated that these measures related to the agents themselves through a link to their internal states. Thus they cannot be identified as reductionist measures. (Chapter 4);
- The proposition of a methodology to understand a manufacturing process, populate the framework with agents of interest, take complex system measures and validate the definitions and observations (Chapter 5);
- Case studies were carried out on a variety of processes in a manufacturing company, investigating issues ranging from the operational to the strategic (Chapter 6, 7 and 8). In each case insights were gained that could not have been obtained from the use of the surveyed tools of the “operational effectiveness” worldview. The implications for the pursuit of “absolute excellence” in production systems was also explored, with the concept structures supporting unobstructed flow featuring heavily.

The rest of this chapter will focus and reflect on the research questions in support of this thesis, and the potential for application and further work in this area.

9.2 Responses to the research questions

Research Question 1

Does the literature on "excellence", especially as "operational effectiveness" challenge, complement or ignore the complex systems view of the manufacturing company?

The literature survey undertaken indicates that there is actually very little linkage between operational effectiveness of a notion of world-class manufacturing and the complexity science literature. This has been supported by the keynote speech by lean production "guru" Daniel Jones at the 2002 conference of the Manufacturing Complexity Network in Cambridge, UK, (Jones, 2002) who stated that complexity science in industry was not providing a foundation or explanation for the new frontier of manufacturing excellence that his own research has documented (Womack *et al*, 1990; Womack and Jones, 1996; Hines *et al*, 2000). This thesis has subsequently shown that complexity science can provide useful measures that in turn can provide novel insights into researchers' understanding of manufacturing processes.

World-class manufacturing is widely documented as a set of tools and this has been built into various "operational effectiveness" frameworks focussed on "variability reduction". The principal ones are:

- Lean production which has an emphasis on waste removal and the integration of organisations along the flow of a value stream, from the perspective of the customer;
- Six sigma which has a strong emphasis on capable quality processes, to create value mutually for the producer and consumer;
- Agility which emphasises the provision of exactly what customers want, when it is wanted, often using computers to manage the high variety implied by this;
- Business process re-engineering with a focus on an owned process, aligned across organisation boundaries from the perspective of the customer.

There is no neat classification of these, and they all pertain to similar final objectives and achievement of performance measures. Packaged into methodologies of their own, the more recent literature shows evidence of synthesis of tools and techniques into a few governing rules and principles. There is also an increasing emphasis on separating tools from the philosophy of which they are supposed to be an embodiment for a given set of circumstances. This reduction of “operational effectiveness” into its constituent or tangible/observable parts appears to have led to loss of the “operational whole”, first observed as an emergent phenomenon in the International Motor Vehicle Program and subsequent studies of the differences between lean and traditional western industry (Womack *et al*, 1990; Andersen Consulting, 1993; Gerwin, 1993, Rommel *et al*, 1996).

The complexity literature has three starting points that have now synthesised into a field that is still very broad, but can be put under the umbrella of complexity science (section 3.4). The in-roads made by complexity science into manufacturing are not significant when compared to the lean or “variability reduction” movement:

- The origins of complexity as an area of management science as a source of improvement via the reduction of complexity in organisations. The state of the art in this area of study was the science of cybernetics. The contribution of this field was the concept of variety and information. When complexity is under control there are measures for actual variety being within an acceptable as-designed bandwidth of requisite variety for the organisation;
- Applying the scientific models of deterministic chaos produced by non-linear, autonomous first order differential equations. These have been taken up both by metaphor and mechanism by researchers. This area of study is rich in measures but they are not widely understood or disseminated in the context of operational effectiveness;
- Computer modelling of agent populations. This has been widely applied to specific problems, with the explicit objective of improving performance as measured by the current view of operational effectiveness. There has also been a fusion of some of the nomenclature and concepts of software development, complexity science and

manufacturing agility in the concept of Holonic manufacturing. This is, however, only one of the aspects of the development of manufacturing science, and is not a pivotal or prevalent view of “operational effectiveness”.

The inclusion of the characteristic parts of best practice manufacturing in the literature of complexity science in industrial applications has been minimal. For the most part, it is restricted to the speciation of companies using best and other practices in a competitive landscape. Very little of this research seeks to characterise the nature of the best practices in complexity science terms. The complexity literature maintains the concept of the system as being emergent and whole, and therefore unsuitable for decomposition into lists of their parts (unlike conventional “operational effectiveness”).

Based on this evidence, it is possible to reject the null hypothesis since there is no evidence that complexity science has already influenced “operational effectiveness” to the point that further input from complexity could possibly provide the new insights sought from this research.

Research Question 2

Do the current measures of “excellence” support a complex systems view of the manufacturing company?

The survey of literature indicates that performance measurement has not embraced complex systems in measuring the manufacturing system. Conventional measurement of manufacturing systems has been focussed on the linkage of the highest levels of results (outcome measures) from a strategy to the lowest sensible level of operational analysis and control. The causal rationale is that if “we know what strategic outcome we want to achieve, what operational performance do we need to elicit to ensure that we get it?”. This is either explicit with balanced scorecards, or implicit and bottom-up in the form of pursuing best practices and six sigma programmes in particular (section 2.2.2)

The closest evidence of an overlap between conventional measurement and complexity in action is the study “Understanding performance measurement systems using physical science uncertainty principles” by Palmer and Parker (2001). A number of complexity science phenomena are offered to give some insight into the success of performance measurement. As such it is a very important and unique paper (section 3.5). One of the conclusions drawn by Palmer and Parker is that the uncertainty sciences make greater use of aggregation and the emergence of a whole, giving some insight into why certain performance measures that copy these traits are better than others.

Approaching this question from the starting point of complexity science, the choice of what to measure in an organisation is also not readily informed by complexity science. Complexity has principally contributed the idea of fitness from evolutionary biology. This is an alternative worldview for the organisation, used to describe the efficacy of a strategy-making process via the particular problem of the pursuit of a set of desirable organisational “genes” (the outcome of operation of which is a good location on a fitness landscape). Fitness is any conventional measure of “operational effectiveness”. The new insight comes from the adopting fitness landscape framework and the notion of genetics. This helps with the process of change and as a language for crisper strategy making and deployment as a set of capabilities to acquire (section 3.4). It is not a measure of the inherent complexity of the company or its processes.

The complexity reduction branch of complexity science has a focus on variety and information in the cybernetic model of the different processes of management (regardless of how they are encoded in an organisation form). This is related to the idea of homeostasis in spite of variety amplification from internal and environmental disturbance. Whilst requisite variety for the management process and transmission between processes provides a measure for the efficacy of the control system and general health of the organisation, it has not been readily related to the conventional measures that the business may already be using, and is a parallel measure of process performance (section 3.2).

Looking operationally, the entropy measure devised by Frizelle and Suhov (2001) can be related to flow in systems, which can be related to time-based measures of performance (section 3.5). For a given mix of products and processes, there is no equivalent conventional measure of “flowability” in conventional performance measurement literature, which was found to be lacking. This is despite the almost universal and dominant focus on the process in current conventional “operational effectiveness” thinking (see section 2.3.2), as well as the complex systems view of Frizelle and Suhov (2001). A similar conclusion can be drawn for structure and organisation design (despite its coverage in “operational effectiveness” literature), as discussed below.

Similarly, the literature survey did not reveal a conventional measure in use for the structural complexity of organisational design. There is no formal vocabulary for connectedness between agents from conventional performance measures and for this reason Q-analysis Atkin (1974) was selected as a complexity science measure for further investigation.

The lack of extensive cross fertilisation of ideas from complexity science into operational effectiveness or vice versa is further support for this thesis.

Research Question 3

What are the agents of interest in a complex manufacturing system, and what are their interactions?

The operational effectiveness literature provides some insight into the agents of interest in a complex manufacturing system (section 2.3). It is in the provision of processes to ensure that value is created for customers with a minimum of waste, by strong emphasis on learning in people rather than the earlier focus on new technology or centralised control (section 2.3.2).

As discussed in section 4.1, the outcome of the work in this area has been the creation of an original three-tiered set framework for Entities, Activities and Resources. This has been based upon the typical definition of entities in discrete event models, and also uses the constituent parts of the IDEF₀ definition set. The important component parts are apparent to the user of the

framework with a background in modelling or its essential precursor of process mapping. The three sets are (section 4.1.2 and figure 4.3):

- Entities output from the system (the purpose of the system). The operational effectiveness literature provides some guidance with its focus on value as perceived by the customer. This has been interpreted as the “product” output *i.e.* the purpose of the system;
- Activities that Entities (or their constituent parts) must undergo to successfully create an Entity for a customer of the Activity set. Reflecting on the process orientation of the current view of operational excellence, the definition of an entity in terms of the activities it undergoes to completion is in keeping with this. By implication, the relation between the Entity and Activity sets (called R_{EA}) is also very important.
- Resources that are allocated to carry out an activity. The view taken of the resources in the case studies has been people working in the activities, as the emphasis of “operational effectiveness” literature is increasingly inclusive of the human element, and less focussed on assets in the form of specific technologies *etc.* This is also a feature of the type of processes featured in the case studies, which are not particularly asset intensive. The R_{AR} relation between the Activities and Resources is therefore the deployment and provision of Resources to carry out the Activities. As such the Resource set membership is must therefore be both important and complex insofar as a complex structure is created.

Resources are the principal set afforded agent status by the complexity-influenced model, and they remain the agents of interest in the EAR framework proposed by the thesis. Given that agents have internal rules, communicate with other agents and have defined states, both the complexity measures used in this thesis support the Resource as the principal area for interest. This thesis therefore differs from holonic manufacturing, where all sets of objects in the model are afforded agent status.

Their interactions are defined by the interrelations of these three sets, in terms of the incidence matrices established for the R_{AR} and R_{EA} relations.

As with modelling, the selection of the set memberships within this framework remains a difficult decision. There must be no relevance lost in defining the set memberships, *i.e.* the set should contain all of the agents of significance, and preferably not include any redundant agents (the latter is not as critical). The definition of "significance" (as with modelling projects) is problem definition dependant. In the case of this framework (supported by operational excellence) it can be universally related to the establishment of flow in the sets of Resources carrying out Activities to represent the flow of Entities.

An example of the problem definition being for other than flow efficacy arose in the Ink and Solvent Delivery Business case study (section 8.4.4), where risk was considered to illustrate the application of the framework to longer term, more strategic issues. In this case it created an inherent conflict in the case study, requiring the modification of the set definition when this topic of flow was not the prime consideration.

It has been established what the agents of interest are in a complex system, and it has been ensured that this is consistent with the view of the manufacturing system (by reference to a survey of contemporary description and modelling techniques in section 2.5). The interaction of the agents has also been carefully defined. This then addresses research question 3 and supports the thesis, by showing that the conventional literature makes very limited use of agents, and by providing a framework for complexity-influenced measurement to be described in the next research question.

Research Question 4

Using complexity science, what are the patterns of operational effectiveness in terms of both structure and behaviour? How can they be measured for study?

One of the most important patterns of complex behaviour in operational effectiveness is the behaviour of efficient flow of customer value. Using the framework described above, this is the creation of (customer-value) Entities by mapping members from a set of Activities (as a process) onto them, carried out by Resources. An effective flow is one with few obstacles, achieved by a reasonable channel bandwidth since it is assumed that capacity has an associated cost to it (section 4.4). The measure of flow efficacy identified and used in the methodology presented in Chapter 5 is based on the entropy of the information required to describe the queue and state behaviour of each activity. This is found by observing the physical resources serving queues of entities with a particular requisite activity. There is evidence in existing literature and in the case studies (sections 6.4.1, 7.4.1, 8.4.1) of the insight that this can provide. This was shown explicitly in section 7.2.1 and 8.2.1, where high entropy was associated with the process bottleneck. Chapter 7 also showed that both information and materials (documents) can make up queues, and that it is important to observe the right type of queue. The methodology has formalised the application of this technique. The observed queue servers are made consistent with a set framework from which patterns of structural complexity may be observed.

This measure of flow efficacy has a number of advantages. It is additive between activities and within the states/queues observed on each activity. This allows direct comparison of the magnitude of flow obstructions across and within the activities observed, and an unequivocal priority list for causes of ineffective operations can be made between all stakeholders. Examples of this were given in sections 6.4.2 7.4.2, 8.4.2.

There are a number of solid examples in the case studies, where this measure of flow tells the researcher more than can presently be obtained from using lean tools of value stream mapping and visual management. These are summarised in sections 6.5, 7.5 and 8.5.

Complexity In Structure

The other pattern of complexity as structure in the framework of agents is more complicated, since there is no single measure of efficacy of a structure, and the business strategic implications of structures have to be considered for the given defined sets and the implied relations between them. The dimensions of strategy have been defined by Hayes *et al*/(1988) as being ten interconnected topics (see section 2.2.1). All ten of these are relevant to the case studies (see figure 9.1), and whilst a good/bad indication is not as obvious as with flow (*i.e.* all bad flow is bad), the structural insights from Q-analysis are no less valuable.

<u>Hayes et al (1998) topic</u>	<u>Precedent for Q-analysis application</u>
1. Provision of capacity	N/a
2. Capacity split between capabilities/facilities	Chapter 6 and 8 - Standard work skills dispersion
3. Equipment and systems selection	Chapter 8 – Equipment redundancy and supply risk
4. Make or buy	N/a
5. Human resources (people) policies	Chapter 7 – Job re-design
6. Quality Assurance and control	N/a
7. Planning and inventory control	Chapter 8 – Process knowledge sharing across departments by cross-skilling
8. New Product Development	Chapter 7 – Engineering Change Control
9. Performance measurement inc. rewards	Chapter 6 – Overtime payments as an alleged driver for localised sub-optimal flow. Chapter 7 – no visibility of performance measurement for stakeholders.
10. Organization structure and design	Chapter 6, 7 and 8 – who carries out which activities in processes

Figure 9.1 – Case study insights summarised from and applied to Hayes *et al*/(1988)

The other aspect of strategic structure in “operational effectiveness” investigated has been the risk posed from polarisation in these two mapping relationships (section 8.4.4):

- Broad spread of entities requiring a single activity and/or an activity requiring a particular dedicated resource (structural redundancy and survivability in some fault condition hazard of the system);
- The sharing of process knowledge (*i.e.* effective structure design in steady state operations, where the hazard is constantly present).

It is certainly possible to speculate that if a system is represented as having a higher risk (*i.e.* poorer structural connectedness for the problem under consideration) in one or both of the above relationships then it may be closer to a catastrophic event/the onset of chaos. The structural Q-analysis measure applied to risk may provide some reassurance to the structural stability of the system with a particular relational geometry.

Using A Pair Of Measures

The joint use of both measures has yielded different sets of results across the three case studies. This supports the thesis by the varied insights that they have provided.

In Chapter 6 there was a significant correlation between eccentricity and flow obstruction, indicating that the obstacles to flow were related to the clustering and polarisation of skills in the employee structure, and specifically the disconnection of adjacent activities in terms of the employees doing them.

In Chapter 7 there was not a strong enough relationship between the two measures for a significant correlation to be demonstrated. Nevertheless, the biggest obstacle to flow was also the most disconnected from their associates in terms of activity sharing. Further integration of this role (the ECN Administrator) into the activity structure coincided with a significant reduction of flow obstruction in the system.

In Chapter 8 there was further (anecdotal) evidence of how flow is related to how effectively a skill is shared in a population of resource agents. There was also a counter-example. This was a

case where poor definition of what constituted a standard work skill led to an example of poor flow in what had the outward appearance of a well-distributed skill. This demonstrates not only the importance of crisp definitions of set memberships but also that the measures tell us different things based on a common set definition.

Where poor structure accompanies flow obstruction (Chapter 6) the measures agree. When structure is one of a number of contributory factors to flow obstruction (Chapter 7), there is still some agreement between measures. The same measurement pair can give some examples of outright disagreement (Chapter 8), implying that factors other than skill distribution are driving the flow obstruction. Set definitions notwithstanding, absolute queue server capacity is another example of this. Here the degree of skill dispersion would not affect the total capacity to serve queue arrivals at any one time. In a case such as this, however, the state observations in the entropy measure would be MAKE states, and the queue only component of the complexity measure for that server would dominate the entropy value.

These two complexity-informed measures can therefore be said to be orthogonal (*i.e.* they carry different information). Thus it can be concluded that both measures carry inherent value and that a less rich insight is gained by the researcher using only one or other of these measures with the framework.

Research Question 5

What would a complete complexity-influenced model using measures look like, and how would it be applied?

The complexity-influenced model is the synthesis of the novel framework (see research question 3), the use of the pair of complexity-based measures together (see research question 4) and a methodology for its delivery. This model has been proposed, operationalised and tested successfully on three different types of process system.

In support of this thesis, the model has successfully given insights that would not have been available from the conventional measures and tools of “operational effectiveness” used in isolation. This disproves the null hypothesis set out in Chapter 1. In drawing this conclusion, it must be acknowledged that the model presented to support this thesis is based on this researcher’s distillation of “operational effectiveness” and that this thesis must be seen to develop rather than refute the principles of “operational effectiveness”. They are, namely:

- The concept of value added as the output from a process, from which the Entity was placed at the “top” of the framework;
- The concept of the Entity as the sum of a series of value added activities, from which the Activity as the building block for the entity was derived in the framework (the R_{EA} mapping relation);
- Critical capacity constraining resources as the starting point of a minimum set of resources to carry out the activities to enable the flow of entity creation;
- The concept of standard work to prescribe the mapping between resources and activities (the R_{AR} relation).

However, there are also some important philosophical differences:

- The “operational effectiveness” view of a top-down split of activities is inherently reductionist, and the loss of the whole is implied. To overcome this, the conventional literature takes a simplified view of the concept of value added. The complexity view is more bottom up with agents creating an emergent phenomenon of an entity through carrying out activities;
- “Operational effectiveness” also implies the reverse of the above statement, *i.e.* that building blocks from which variability has been removed can be added together into larger, scaleable processes without any emergent phenomena, and that the bigger system will “look after itself” if you get the small unit processes right through standard work operations, and use simple enough rules when connecting unit activities. The Visual Management (VM) board is case in point of this *i.e.* that a unit activity can be studied as a separate unit;

- The concept that single, static “snapshot” observations explain enough about the systems (The Value Stream Mapping technique is a good illustration) for a meaningful understanding to be developed. As a consequence, there is no overall measure for “flowability” in lean systems despite the tremendous importance of these.

Illustration in the case studies in sections 6.5, 7.5 and 8.5 show how the complexity influenced model presented in support of this thesis improves on the insight of the limiting worldview of “operational effectiveness” presented above and in detail in section 2.3.

Research Question 6

Can this complexity-influenced model be placed on a spectrum including strategic planning and operational execution?

The use of the complexity-influenced model in operational situations has proven highly successful, and this thesis has been less so with strategic decision-making.

Moving out of the domain of operational execution, the “operational effectiveness” view has also had difficulties in its successful application away from materials transformation with their characteristic resource concentration on repeatable tasks, operating in limited environmental turbulence (the *heijunka* level schedule). By employing the same “operationally effective” lean principles it has been shown that this can be translated to product development by best in class companies like Toyota and leading aerospace companies (*e.g.* Sobek *et al*, 1998; Costanza 1996; Murman *et al*, 2002). The complexity-influenced model appears to have made a relatively simple transition into the slightly more strategic information-processing domain, with its successful use in Chapter 7 in the Engineering Change Note process (see section 7.5).

However, as with “operationally effectiveness” tool and techniques, it is unclear in addressing key strategic issues such as those raised in Chapter 8 how the model adds extensive new insight. A more detailed discussion of this is to be found in Chapter 8, where there is some evaluation what

benefits were actually brought, and only a brief summary is made in this chapter. Where appropriate they are discussed in context in response to the earlier research question 4.

Research Question 7

Can this complexity-influenced model show researchers and practitioners what "absolute excellence" would look like, without empirical bias of specific approaches or "best practice" prescription of tools and techniques?

The merits of the complexity-based measures in different contexts are covered in research questions 4, 5 and 6. To conclude the work of this thesis, it is appropriate to speculate about the broader implications of the findings that support the thesis before returning to the scope of the thesis and how it may be applied and extended (see Section 9.3).

"Absolute excellence" would arguably manifest itself on the complexity-influenced measures as a framework structure enabling flow without obstructions. This would be without any IDLE, SETUP or BREAKDOWN states (implying no subsidy to the perfect flow from an excess of capacity) so abhorred by lean production systems. As a performance measure this is both a process and outcome measure.

To achieve perfect flow in a way that meets the requirements of the market being served (recalling the dimensions of competitive strategy reviewed in section 2.2.1), some consideration of flexibility of response must also be made. As shown in Chapter 2, debate on the dimensions of flexibility faltered when the "one best way" of lean manufacturing was able to outperform conventional organisations that were affording flexibility by making trade-offs (recalling the PPMX matrix and PCS cube in section 2.2.3). The competitive race then became less about strategic trade-offs and more about pursuing operational effectiveness with a prescriptive set of tools and techniques to be adopted, and the reductionist view presented in the literature at the time of writing this carried the day.

The research of this thesis supports the view that to understand how to deliver increasingly flexible responses ("absolute excellence"), companies' markets must be viewed as an increasingly non-linear competitive phase space. As a consequence, a more detailed understanding of the complex system behaviour of the manufacturing company is required.

This requisite understanding is simultaneously of the whole manufacturing system and a measure of the complex structure that will produce the desired behaviour, getting closer to the "mechanics" of the systems under study as a consequence. Finally, for a complex system, simulation is an important capability as this is the only way in which experiments about both large and complex systems may be carried out. The complexity-influenced model presented in this thesis supports all of these anticipated requirements for continued "operational effectiveness".

In research question 5, the "operational effectiveness" approach was summarised as reduction of value adding processes into simple building blocks of standard work. Each building block then has its own inherent variability reduced through process control and quality techniques. The blocks can then be built up into larger systems using simple rules, recalling the DNA of the Toyota Production System (Spear and Bowen, 1999). It has been shown by companies like Toyota that the better a company is at this precise construction of the building block and its interconnection, the bigger the systems it can construct in this way. To an "operationally effective" company, flexibility is necessarily offered by configuration (interconnection) use of these building blocks.

The complexity-influenced model uses these ideas of value flow as its starting point only and does not rely on this latter scaleable property. (That said, its own effective application benefits from the type of crisp set definition possible from standard work operations). This point is made because the changing competitive markets in which companies operate (their phase space) may affect the scaleable limit of the "operational effectiveness" reductionism, and hence their competitiveness. However, having now studied this "operational effectiveness" it must be remembered that one of its strengths over its predecessors is its willingness to reshape the incumbent constraints around itself to support the continued use of its approach, rather than make sub-optimising trade-offs.

9.3 Further work

9.3.1 Practical application of the complexity-influenced model in manufacturing systems

The model has now been applied to three different processes in the design, manufacture and supply of products in an actual manufacturing business (Linx Printing Technologies plc). Whilst it has been possible to define and populate the Entity Activity Resource framework and to test the relationships of interest R_{EA} and R_{AR} , it has not been possible to consider a whole single EAR framework. When this was attempted for the Ink and Solvent Delivery Business, the same EAR definitions that provided a rich set of relations for one line of enquiry did not create a rich structure for another. Hence the R_{EA} was modified by changing the Activity set (with implied changes to the resources following).

This leads to the point that is also apparent in modelling projects, that the problem statement is perhaps the most important part of using the model because it influences the definition and population of the EAR hierarchy and the measures made up on it.

Having stated the shortcoming of the case studies trying to test the EAR hierarchy, it is also important to state its success in unifying:

- What the customer wants from a process (Entity);
- How the process is mapped to work (Activity);
- How the process is to be physically carried out (Resource).

Whilst this has been done through a number of mapping tools, using the complexity measures is the first time that this description can be carried to actually take measures of the performance of the process.

The joint measures from complexity have made a definite contribution to understanding a manufacturing process' behaviour and structure and their cross-pollinating influence on each other. The measures do tell the researcher more than conventional measurements do, and their use together has revealed that some root causes of poor operational performance can be better understood through their joint use. The success of the measures is that they do augment rather than replace existing performance measures. In their current form with the Entity Activity Resource framework, it is the opinion of the researcher that they could now be used actively in manufacturing processes.

9.3.2 Further Research

A full test of the EAR framework would satisfy the question of its suitability beyond the case studies already carried out successfully on parts of the whole. It would also allow the product space of the framework to be exhaustively explored, with "triangulation" of the framework (*i.e.* test the R_{ER} relation) and also test the R_{AA} relation to see what effect sequence dependency have upon structures and their operation.

This further experimentation would be supported by more extensive use of slicing indices in incidence matrices, allowing sensitivity analyses. It would be possible to look for complex behaviour in the more classical chaotic domain of small changes, sensitivity to initial conditions *etc.* in structures and their resulting flow behaviour (Queue server entropy would provide this).

With adoption of classical chaotic measures, the onset of chaos could be studied more closely and the sets of entities, activities and resources interacting could be measured in terms of the dimension of strange attractors, and the networks of resources coupled and treated like NK Boolean networks. Once established, this could be developed with agent-based simulation to explore evolution of the process. With expanded rules (over and above the mapping relations) determining the interaction of agents, then decentralised control and different scenarios could be explored, and their stability/adaptability and flow behaviour set as hill-climbing goals. If

successful, this will provide a firmer connection between business management and mainstream complexity science.

Once a fuller range of complexity measures has been looked at, then the implications of the effect of complex behaviour on the manufacturing system should be better understood. This could then support the incorporation of complexity measure(s) into an expansion of a balanced scorecard. In this expanded framework, managers could perhaps have an additional insight into the efficacy of flow, the stability of structure, and / or the sensitivity to initial conditions of the processes they were managing and improving. Retaining a framework like the Entity Activity Resource proposed in this thesis would ensure that insights would be extended into the critical relationships between what customers want (value), and the design and operation of the process by which value is delivered to them

APPENDIX A - BACKGROUND TO SINGLE PIECE FLOW

ASSEMBLY OF PRINTERS

A.1 Business Strategic Context

A.1.1 Background of manufacturing process

The products

There are two generic printers and two generic printheads (with common parts) acting as product platforms. Each is customised to printing application and customer, by combination of printer, printhead, ink choice, language variant of software and keypad, *e.g.* Figure A.1.



Figure A.1 – Example printer with printhead

Each shipped printer and printhead contains around one thousand separate component parts. Manufacturing operations are restricted to assembly and test, with all parts being purchased from suppliers and subcontractors. From the one thousand specified parts per printer and printhead, the assembly process handles three hundred discrete parts. The rest are integrated in the form of printed circuit board assemblies (resistors and other passives, connectors, chips *etc.* are placed onto the PCB by the supplier) and limited sub assembling on mechanical parts *e.g.* mouldings with pipe barbs fitted at the moulders.

Five thousand printer and seven thousand printheads are manufactured each year (the excess printheads being sold as spares). This figure has been stable for a number of years.

The plant and its people

Over sixty operators are employed in the plant, supported by a single supervisor, one inventory controller and one production planner. There are also buyers and production engineers supporting part and process quality and supply continuity. The manufacturing plant runs for 35 working hours, four days per week (Monday to Thursday), single shift. All operations take place in one building, with printheads built and calibrated on the first floor and the printer cabinets build and integrated with printheads and tested on the ground floor. The organisation is extremely flat, with horizontal job growth the only route for operators. The supervisor is a senior member of the management team for the manufacturing group, and it is unlikely that a direct internal promotion from operator to supervisor would be considered.

Lean manufacturing was first introduced six to eight years ago following an explosion of product complexity with the rapid growth of the company. The pre-lean manufacturing system had comprised a series of batched sub-assembling operations, each initiated by its own works order, for whole units. The lean implementation was a single piece flow, whereby whole units are built up by the flow of single units through work cells, with each cell connected by a kanban of ten parts. This has been extended to include the line-side replenishment and kitting from stores of component parts, depending on their value and bulk volume.

Before the initial shift to lean manufacture some years ago, the following "pre-lean" problems were experienced:

- poor delivery performance;
- poor traceability and complicated shop floor control (the multiple works orders could not be kept up to date);
- a higher number of defects per unit.

The results of the implementation of standard operations, work cells, single piece flow, level scheduling and kanban/line-side replenishment were the transformation of:

- Delivery – consistently hitting over 90% of products on-time;

- Lead time – all inventories fell;
- Visibility - by using a single works order per printer or finished spare, a single graph shows the schedule conformance of the entire manufacturing system;
- Quality – fewer defects per unit and also better field reliability.

It is now possible to build all products to order, a strategic capability that is still being explored. The current reality is that a mixture of specific "stranger" products are mixed with "runner" products featuring the most common printer configurations of inks, languages (keypads). The "strangers" are made to order exclusively; the "runners" will be a mixture of confirmed orders and speculative builds based on forecasts.

Since the improvements of the introduction of lean production some years ago, further scope for improvement has been identified. This case study was motivated by the observation that one area of the operation appeared to be a bottleneck, as it required large amounts of overtime to maintain throughput. Moreover the management view was that the problem lay in the distribution of skills of the operatives involved. As a consequence the area worked out of synchronisation with the rest of the production system. This is one of the two parts of the process where discretionary skills of interpretation are used (to assess print quality). Also, a complete product is worked on from start to finish by one operator, rather than a balanced flow line of standard operations. In one key activity of calibration many parallel servers draw from one queue because of a long activity cycle time.

A.1.2 Objectives of manufacturing process

The main objective of the manufacturing process is to make the correct range of high-quality printers available for dispatch. As a secondary requirement, waste in the form of excess labour and inventory is to be minimised.

The performance in achieving the process objectives are measured by two cross-functional meetings of senior managers in the business:

- Delivery performance of the proportion of printer and spares orders available to ship when required is reviewed by a commercially focussed team at the Orders and Sales Forecast meeting;
- Quality of the products shipped is measured in terms of its "Out Of Box Quality" at commissioning by a technically focussed team at a weekly meeting called the Consolidated Quality Meeting. Representatives from Manufacturing, Design Engineering, Sales and Customer Service attend.
- The system fill level (number of live works orders in the manufacturing system) is reviewed daily by the manufacturing management team, comprising the:
 - Manufacturing Director;
 - Purchasing and Logistics Manager;
 - Production Supervisor;
 - Manufacturing Engineering Manager.

A.1.3 Discussions with stakeholders

The following interviews were conducted:

- MR (Production Director) - views that the operating costs of the assembly and test operation are a small part of the total manufacturing budget and should not form a high priority for his management team. High output quality and responsiveness from the operation are far more important. Operational performance is good considering the late and patchy arrival of confirmed orders from the sales order-processing group.

- MB (Sales order processing team leader) – acknowledges that confirmed sales orders have a highly variable arrival, and result from the company's distributors who order the products. She feels that they should not produce any problem in manufacturing, given the excess capacity in the form of the number of operators employed. If there is ever any need to "catch up" because of late order confirmations, manufacturing should have the slack to do so;
- BW (Production Supervisor) – does not view the operation as having any control problems, but feels that materials availability from suppliers and late/sporadic order confirmation are major disruptions to his operation. He takes pride in supervising the sixty-plus operators directly, and feels that this is only possible because of empowerment of the shop floor and a degree of self-organisation by the operators made possible by the discipline of skills matrices. The sharing of skills throughout the process is actually reasonably robust;
- BC (Purchasing and logistics manager) – acknowledges that late deliveries can cause problems. However, he would like to see the impact of poor supply chain performance against all the other causes of disruption, especially internal ones such as absenteeism in "key operators" (possessing critical skills);
- PE (Manufacturing Engineer) – feels that the functioning of one of the production departments is out of control. The work content of this area is clearly understood and there is excess capacity in the area. Even so, "management" is tolerating excessive overtime working. As a result, some of the operators working there are earning more than the production engineers!

Based on the discussions with stakeholders, the issues to be explored by the study are as follows:

- What actually obstructs the flow (and hence delivery performance) of the area? What are the relative impacts of problems in the supply chain and working practices within the operation?
- What is the characteristic nature of skills dispersion currently, and can this be compared to a set of best practices?
- What is the disruption of late arrival of the confirmed orders on delivery performance?

A.2 Detailed operation of manufacturing process

A.2.1 Process mapping

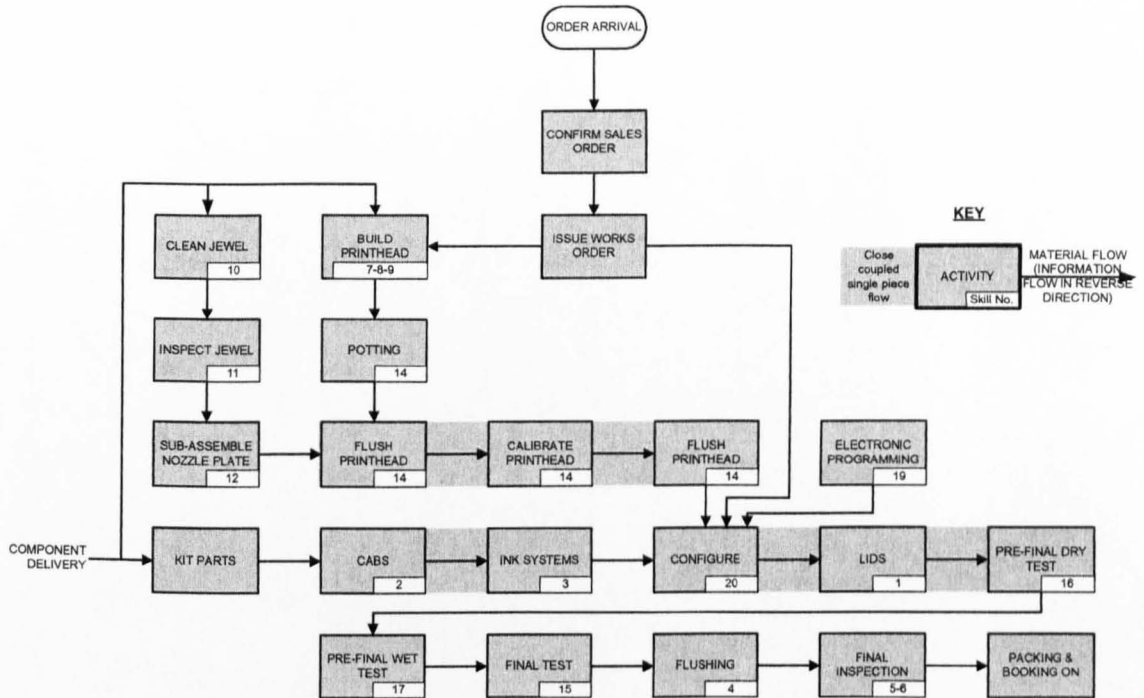


Figure A.2 – Printer and printhead assemble and test.

An order arrival from a customer (distributor who resells the product) is dated and confirmed by the Sales Order-Processing group (Fig. A.2). This confirmed requirement is then passed to the production planner, who issues works orders for this product. There is also a Materials Requirement Planning (MRP) loop whereby adjustments are made to a Master Production Schedule (MPS) for buying in conjunction with the sales order processing group and product managers, orders are placed on suppliers *etc.* This loop is outside of the scope of the study.

The works order is then placed on the Configure (Skill 20) activity for printers. A works order is also issued to the Build Printhead activities (Skills 7-8-9), if the printhead required by the works order is a:

- "Stranger" and not in an internal process kanban store;
- Spare printhead (to be sold separately without a printer).

There is a replenishment trigger for “runner” printheads with internal kanbans established.

A printhead is then built and potted. A four-hour wait time is required before the heads can be potted and an eight-hour wait is required after the potting is completed, to allow sealants and potting compound to cure. The printheads are then taken and processed by one of a number of parallel single piece flows where the head has a nozzle plate fitted and it is flushed (Flush Printhead 1), the head is then calibrated and flushed again (Flush Printhead 2). This is carried out on a head by one operator, who carries the printhead from flushing rig to calibration rig and onwards until the head is either rejected or ready for transfer to the printer build area. This all within the scope of work of Skill 14, and it is this area that has high levels of contentious overtime working. Assuming it is fit for purpose, it is then ready for use on a printer.

The nozzle plate is prepared off-line in a small clean room. The jewel (a small industrial sapphire with a tiny hole drilled in it) is cleaned (skill 10), inspected (skill 11) and then built up into a nozzle plate (skill 12).

In the printer cabinet building area (downstairs), high value and bulky parts are kitted from stores in units of ten generic printers. Subject to the demand specified by works orders, specific kits will be pulled and replenished (kanban-style) by stores.

A kit then flows, a printer per station, round a U-shaped single piece flow cell. Electrical enclosures are first built up (Cabs, skill 2, three standard operations in series), next the ink system is built into the same stainless steel enclosure (Ink Systems, skill 3, four standard operations in series). The printer is then configured to the requirement of the works orders (Configure, skill 20, two standard operations in series), and from this point the printer has a specific identity. A specific Printhead and Printed Circuit Board (PCB) with software and language variants specified by the works order are added here. The PCB will be replenished to an internal kanban between the Electronic Programming activity (skill 19) and Configure.

This then allows the lid to be built up to complete the enclosure (Lids, skill 1, three standard operations in series), where a keypad (language-specific) is included in this part of the assembly. Finally, the printer is safety tested and started up without ink (Pre-final Dry Test, skill 16, one standard operation) at the last workstation of the cell. All operations in the U-shaped cell take a maximum of ten minutes. Hence when all thirteen stations are fully resourced, a printer should be produced every ten minutes.

The printer then goes into a wet area, where it is wet tested. This is broken up into a set of routine wet tests (Pre-final Wet Test, skill 17, one standard operation with two stations in parallel), and a functionality test of the printer on the ink type that will be used by the final customer (Final Test, skill 15). This test is carried out by up to four operators, who each have a number of test bays. They have a measure of discretion as to how they organise their tests and filling/emptying of their bays. The completed printers are then flushed clean (Flushing, skill 4, one standard operation, three parallel stations). After the printers are flushed, they are then inspected finally (Final Inspection, skills 5-6, two standard operations carried out by two operators working in series or parallel at their discretion) and sent for packing. After packing is complete, the works order is completed and the printer is shown on the MRP system as available to ship.

Based on the process mapping exercise, it can be shown that there is enough theoretical capacity to make a printhead or printer every ten minutes, or 210 printheads or printers per week. Given that annual demand is seven and five thousand items respectively, there would appear at a first glance to be a massive excess of capacity.

A.2.2 Entity-Activity-Resource definitions and set membership

The Entity in this case study is the customer requirement for a printer, expressed throughout the system as a confirmed sales order that is issued to the shop floor as a works order and built into a printer or replacement printhead for a kanban. The entity variety is low insofar as the products

are designed along familial lines with as much as possible part commonality, and common build sequences exist with similar work contents.

The Activities are the process steps detailed on Figure A.2. They have a clear ownership in the form of the skills defined at each activity “box” in the figure (see key), which are tracked as standard operations in a skills matrix. The exceptions are the tasks that are driven by procedure rather than standard operation, and are carried out away from the shop floor by support groups.

The procedure-driven tasks are:

- Confirmation of sales orders;
- Creation of works orders;
- Kitting of parts;
- Packing and booking of printers onto the computer controlled inventory MRP system.

The Resources are the people available on the shop floor who carry out the standard operations. This is the principal variable because the other “artefacts” in the production environment are fixed. These are the workstations, tools, trolleys, storage bins and buildings. There has been a deliberate policy associated with the single piece flow architecture of large parts of the shop floor. Standard operations and dedicated equipment and places to perform each standard operation have been created for the jobs.

A.2.3 Process Aggregation

Minimal process aggregation was carried out. The skills and people possessing them have been represented exactly as described in the actual production system at the time of the study.

The principal simplifications have been made to the Entities, in the form of one type of printer and one type of printhead to be produced. This therefore limits the scope of the study in the dimensions of:

- Product mix changes affecting the response offered from the existing in-process Kanbans;

- Priority and mix changes once works orders have been released to manufacturing;
- The small differences in manufacturability, work content and parts required from suppliers exhibited between products;
- In process kanban buffers will be for one type of part only and not reflect specific printhead or PCB shortages.

The view taken in the study is that the risk to an insightful study and model posed by these simplifications was minimal. The basis for this rationalisation was the stakeholder views, which did not identify these issues at all. Given the richness of scope of the study, this simplification was made.

APPENDIX B - BACKGROUND TO ENGINEERING CHANGE CONTROL

B.1 Business Strategic Context

B.1.1 Background of ECN process

Linx holds the ISO9001:2000 quality management standard, a principal requirement of which is the control of customer/product specifications, from customer requirements through to detailed design realisation. It is also a requirement for the various product safety standards such as the CE marking of series manufactured products such as the printers. The ability to reliably document design intent of products is therefore critical to the safe, legal and accredited operation of the company.

The ECN process is also a one-size fits all control vehicle for the management of Linx, acting as gateway onto the Material Requirements Planning (MRP) system. No new part can have a part number keyed inventory record created for it unless it is accompanied by an ECN. This includes all items in the company. Whilst this is an important feature for anything that is going to affect product quality or safety, it contains redundancy for other items such as consumable items used in production, promotional literature and merchandising, and even some internal (departmental) documentation.

The ECN therefore has many customers. As the company has grown, there has been a lack of focus on the original purpose of the system; namely to ensure that the correct version of parts is used on printers, spares and in inks at all times, and that the rationale for changes to the product range is documented.

B.1.2 Objectives of ECN process

Despite the convoluted use of the ECN process, the objectives of the process at the start of the study are to ensure that:

- The suggested change will not produce any unforeseen consequences in the safety, manufacturability, serviceability, cost or sales proposition of the product;
- Traceability is available when required on all safety or quality critical parts;
- Design changes can be made to products quickly and with minimal effective controls without stifling the participation of all staff;
- Part numbers are made available to all parts. This extends to all parts the business deems important, or expensive/valuable enough to stock and actively “manage”. There is a parallel non-stock purchase route whereby items can be bought directly for the business. Parts falling into this latter category can be costed and accounted for if they are of significant value *i.e.* they are visible to all business functions.

As discussed, many of the items under ECN do not qualify under any of these headings.

However, they do require unique numbers for their parts or documents. Given the broad set of customers and purposes of the system, it is not too surprising that no formal measures existed for the operation of the process. Clearly, the stakeholders all have their own requirements of the system and so agreement as to what are important outcomes from the system would be unlikely.

An initial study based on an analysis of historical ECN arrivals and completions revealed that around 230 ECN's are raised every year, and that the average throughput time of an ECN has been twelve weeks, though much higher in recent times.

The ECN is also intimately woven into most of the change processes of the company; from the first design freeze on prototype component parts to allow subcontractors to quote on them, to the sales of products with their associated marketing publications. However, most of the customers of the system do not require a multi-functional review of the change the originator wishes to make, and changes could be managed within the departments primarily concerned.

B.1.3 Discussions with stakeholders

Because of the large number of stakeholders in the process, fourteen interviews were undertaken, from a potential pool of one hundred and twenty people employed at the site who could conceivably be involved in an ECN. These people were:

- The Engineering director sits on the ECN committee but did not have any strong views about the process or its effectiveness;
- Three engineering functional group leaders. As engineering project managers, their comments on the current system included that there is no feedback or visibility of the ECN once it has entered the system. There are three non-communicating IT systems in use: design tools such as mechanical and electrical CAD; the database of ECNs; and the purchasing Material Requirements Planning (MRP) system comprising Bills Of Material. This is a frustration, especially as there appeared to be no external management of the process - unless in crisis, there is no pace of urgency in the process, and it perceived to be slow and unresponsive if ECNs are not expedited through the steps;
- Three design engineers who are principally originators of ECNs and tend to have limited involvement thereafter;
- The product (marketing) manager for the printing machines felt that he should not sit on the review committee as it was not a good use of his time. He felt that the originators should be more involved and accountable for their change requests;
- The marketing communications manager and his assistant felt that the system was slow. This causes them to "place orders at risk" to compress lead times, in advance of process steps;
- Two people from the technical publications department (part of the customer service group), who write product bulletins and manuals both felt that they are restricted in their ability to complete their ECN actions because of their dependence on other people to comment on their draft publications;
- The buyer from the purchasing group who implements all ECNs in the supply chain and determines when a change will take effect in built product. She felt that the process was

often “out of sequence” and could not start implementing the new parts with suppliers because drawing packages were not complete in time;

- The CAD engineer working in the Engineering Service Group (ESG) who makes drawing changes in response to details of change note. He felt that he was kept steadily busy and had no concerns with the performance of the process.
- The ECN administrator in ESG who administers the whole process and makes Bill Of Material changes when parts are modified and up-issued or superseded by the actions of the ECN. He felt overworked and constantly busy. Despite seeing the whole process, he did not have any conception of a need for process performance measures, or more visibility and involvement from originators. He was not concerned about the perceived pace of the process because the lead-time is “as long as it takes”.

Based on these comments and concerns, the following topics were distilled:

- The process is slow and unwieldy. This results in people doing actions “at risk” to compress additive lead times by concurrency. The contributory factors are felt to include the late completion of drawing packages, and slow response from people commenting and approving technical publications;
- There is no visibility or feedback for the originators and other participants;
- The process is not being managed and does not have a “process owner” or anyone who would recognise themselves as such.

An interesting observation emerged at a workshop held to introduce the study and map the process aside from the interviews summarised above. Even with the ECN procedure in front of the assembled stakeholders, it was not possible at this meeting to get agreement on the actual process. The resulting process map was produced from an in-depth interview with the ECN administrator, by ascertaining what the different parts of the paper ECN form meant and when they were completed and by whom.

B.2 Detailed operation of process

B.2.1 Process mapping

Figure B.1 shows the detailed process for the review, actioning and implementation of an engineering change:

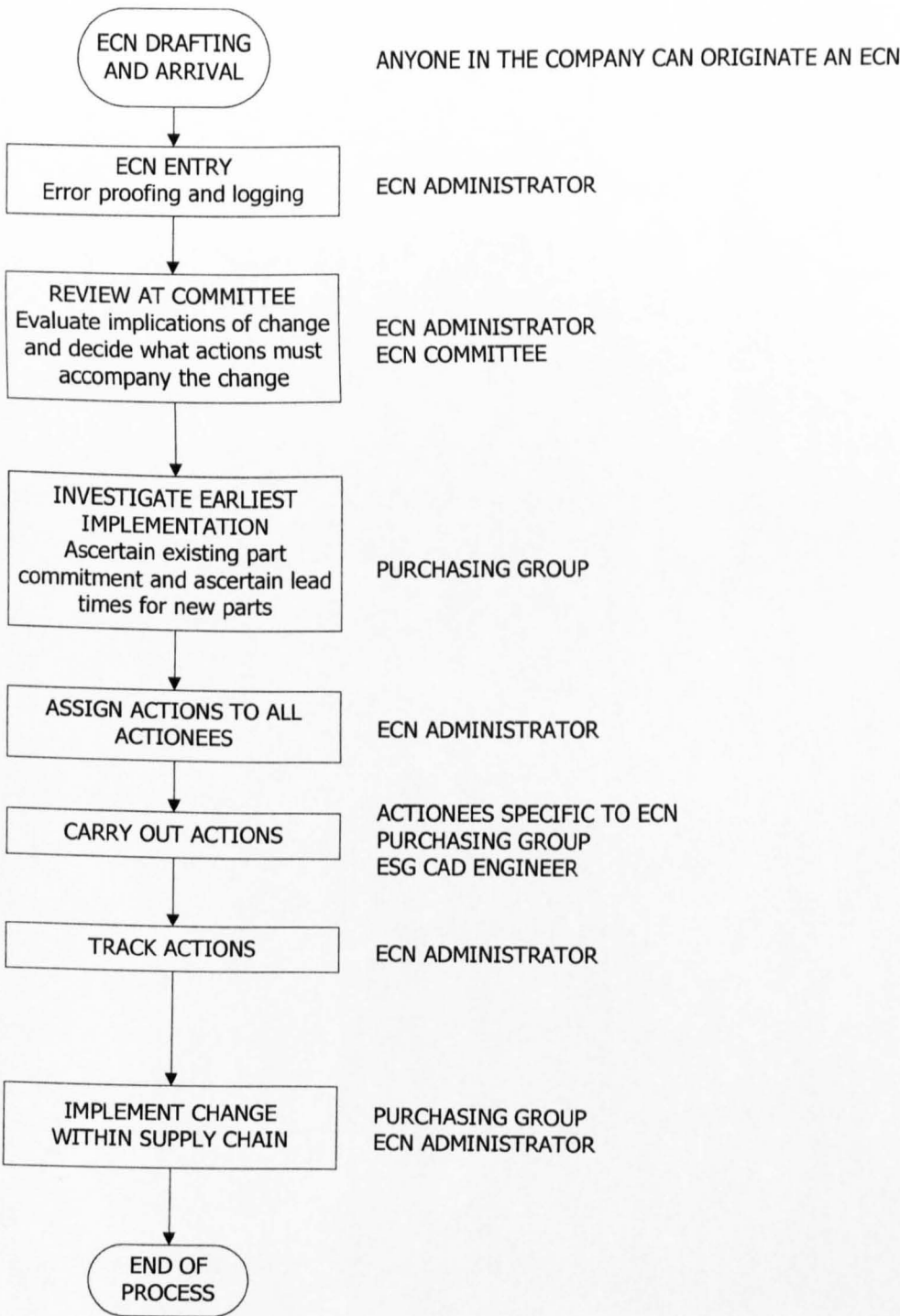


Figure B.1 – Detailed, generic process (with all activities) for all ECN’s. Resource allocated to the activity (on right hand side).

The Engineering Change Note (ECN) system is structured with the aim that anyone in the company can make a suggestion. This includes production operators who see a better way of constructing a printer or solving a particular problem. For this reason, the first activity after the arrival of the ECN is the error proofing of the ECN, to ensure that Bills Of Materials listed as requiring updates *etc.* are correct. The change must also be adequately described to allow functional specialist to consider the change in detail at committee. This review takes place at the ECN Committee, a fortnightly meeting to consider all change requests. The committee assigns actions for all successful ECNs. These changes are divided between the four functional areas represented at the meeting:

- Design engineering may be required to perform drawing changes or other activities;
- Customer service group may need to update manuals or produce and publish bulletins to advise customers of the impending change;
- Manufacturing engineering may need to review build procedures, jigs and fixtures, product packaging and protection *etc.*;
- Sales and marketing may wish to produce marketing materials, or be asked to define a pricing structure for a new product.

After these meetings, ECNs are then forwarded to the Purchasing Group, where a nominated buyer investigates the earliest date that an ECN can be implemented with suppliers. Since all primary components are bought, this will determine when a change can take effect. Certain types of engineering change will be mandatory (*e.g.* for a quality or safety related change) and so will be implemented as soon as new parts can be made available. Others may be running changes, and made as soon as the supply of the existing part within the supply chain has been exhausted. Once this is established, the ECN is returned to the ECN Administrator for assigning the agreed implementation actions to the actionees.

These actions will be varied, but will typically include a bulletin, some drawing updates, and a price change. Where an ECN has been raised for the sole purposes of obtaining a part number, there will be no actions assigned, and the ECN Administrator then allocates a part number. On other occasions, the actions may be marked as "ongoing" to allow the subsequent steps to

proceed. This is a controversial practice because the underpinning assumption made by the committee is that the action has been deemed necessary to implant the change in a controlled fashion.

Actual changes or new products will have an associated Bill Of Materials (BOM). Once the actions are complete, the BOM will be updated. Purchasing group is then free to start issuing the parts (assuming that they have been delivered on time) and it can be made available to customers (either implicitly as built printer or explicitly as a spare).

B.2.2 Entity-Activity-Resource definitions and set membership

The Entity in this case study is the physical Engineering Change Note. This has been decided on the basis that the input to and output from the system may be actual changes made, but that this is neatly captured from the start to end of the process by the ECN artefact itself.

The Activities are the process steps detailed on figure B.1. They have a clear ownership (multiple people attributed to them implies parallel actions are being taken). The Activities could have been more finely resolved, *e.g.* to reflect jig and fixture changes in manufacturing *etc.* but this was not felt to be useful. This is discussed in the following section, and instead the generic boxes shown in Figure B.1 were adopted.

- The Resources are the people in question who carry out each of these Activities. These are the employees in the company, and can include an estimated one hundred and twenty people on the site. It is more than likely, however, that the ECN activities are carried out by a relatively small, key subset (the people targeted for interviews). Also, individuals *per se* are not used as resources, because the activities are carried out more by people in different roles (*e.g.* a committee member will rarely if ever be an actionee because the actions are delegated within their respective departments). The result is that the resource set has been defined in terms of the roles defined in figure B.1, and not specifically as the engineering director or product manager. The other reason for this is that working on the activities of the ECN process is a tiny proportion of the role of most

people discussed, and so individuals' contributions are less important. The only exceptions are the ESG CAD engineer and the ESG Administrator, who work full time on ECNs.

B.2.3 Process Aggregation

In first inspection of the set of Entities, every change appears to be relatively unique. Closer inspection reveals that in fact there are entity "families" in terms of new products, engineering changes to the established product range, or literature and stock items. The impact of these entities in their interaction with the defined Activity set is very similar. Furthermore, all entities will have slightly different resource loading implications:

- Size and specificity of actions given by the committee, and to whom each action is given;
- Actions will be given different priorities depending upon the ECN and other loading of the Resources concerned (ECNs are only a small part of any one actionee's jobs, and this will affect the priority given).

Given this tremendous combinatorial range of possibilities for each ECN, even similar products might not be represented accurately by a discrete number of families of ECN. Also, the objective of the study is to investigate the relationship between process activities and resources. The entities are being simplified to one type of order arrival and routing, with a statistical weighting based on historical evidence.

Certain Activities have been simplified, especially the carrying out of assigned actions, into single steps (in fact it is many steps in parallel), with a statistical weighting applied.

The process has been further simplified by the definition of the Resources in terms of roles of people in the process in place of the actual individuals in question. Within these roles, a small number of representative individuals (across disciplines) carrying out the roles have been selected for study. The involvement of the purchasing group and ECN committee takes place every

fortnight and is relatively brief so they have not been included in the study. The roles defined are shown on figure B.1, and are as follows:

- ECN Administrator;
- ESG CAD Engineer;
- Actionees (other);
 - Product Bulletins (Technical publications);
 - Marcoms (Marketing communications);
 - Manuals (Technical publications);
 - Design Engineering.

B.3 Measure I: Entropy Calculation Worked Example

The entropy calculation (column called "Entropy" in figure B.2) uses equation 4.1 for each line:

$$H(x) = -\sum_{i=1 \text{ to } n} [p_i(x) \log_2 p_i(x)]$$

where x is the queue only probability used for entropy without states. For example, for the ECN administrator there are 18 observations. The first for queue length 16 has frequency 1, and probability $p_1(x) = 1/18 = 0.056$, and $\log_2 p_1(x) = \log_e 0.056 / \log_e 2 = -2.882/0.693 = -4.159$. Therefore the entropy for the first row is $-p_1(x) \log_2 p_1(x) = -(0.056 * -4.159) = 0.232$, as shown in Figure 8.2. Thus the without-state entropy for ECN Administrator is $0.232 + 0.513 + 0.352 + 0.482 + 0.352 + 0.352 + 0.232 + 0.232 = 2.747$.

Equation 4.7 is used for total entropy with-states calculations in the second column of Figure 8.2:

$$H(q,s) = -\sum_{\text{all } q} \sum_{\text{all } s} [p(q,s) \log_2 p(q,s)]$$

Resource	With-States Entropy (Equation 4.7) DOCUMENT QUEUE						Without States (Queue Only) Entropy (Eq 4.1) DOCUMENT QUEUE					
	State	Queue length	Observed Frequency	Probability	Entropy	Total Entropy H(S) all s terms	Total Entropy H(S) all q term {all s terms}	Queue length	Observed Frequency	Probability	Entropy	Total Entropy H(S) q terms only
ECN Administrator	M	16	1	0.056	0.232	2.747	2.747	16	1	0.056	0.232	2.747
	M	18	5	0.278	0.513			18	5	0.278	0.513	
	M	21	2	0.111	0.352			21	2	0.111	0.352	
	M	25	4	0.222	0.482			25	4	0.222	0.482	
	M	27	2	0.111	0.352			27	2	0.111	0.352	
	M	31	2	0.111	0.352			31	2	0.111	0.352	
	M	35	1	0.056	0.232			35	1	0.056	0.232	
	M	36	1	0.056	0.232			36	1	0.056	0.232	
CAD Engineer	M	8	2	0.111	0.352	1.612	1.612	8	2	0.111	0.352	1.612
	M	10	1	0.056	0.232			10	1	0.056	0.232	
	M	12	9	0.5	0.5			12	9	0.5	0.5	
	M	13	6	0.333	0.528			13	6	0.333	0.528	
Bulletins	M	4	1	0.056	0.232	1.803	2.155	4	3	0.167	0.431	1.905
	M	6	6	0.333	0.528			6	3	0.167	0.431	
	M	7	7	0.389	0.53			7	7	0.389	0.53	
	M	8	5	0.278	0.513			8	5	0.278	0.513	
	B	4	2	0.111	0.352			0.352				
Marcomms	M	9	1	0.056	0.232	0.584	2.071	8	6	0.333	0.528	1.572
	M	11	2	0.111	0.352			9	7	0.389	0.53	
	B	8	6	0.333	0.528			11	5	0.278	0.513	
	B	9	6	0.333	0.528			1.487				
	B	11	3	0.167	0.431							
Manuals	M	5	1	0.056	0.232	1.093	2.441	5	3	0.167	0.431	1.481
	M	6	3	0.167	0.431			6	7	0.389	0.53	
	M	7	3	0.167	0.431			7	8	0.444	0.52	
	B	5	2	0.111	0.352							
	B	6	4	0.222	0.482			1.348				
	B	7	5	0.278	0.513							
Design Engineering	M	2	2	0.111	0.352	1.135	1.569	2	2	0.111	0.352	0.986
	M	3	2	0.111	0.352			3	2	0.111	0.352	
	M	4	3	0.167	0.431			4	14	0.778	0.282	
	B	4	11	0.611	0.434			0.434				

Figure B.2 - expanded calculation for entropy with and without states.

B.4 Measure II: Q-Analysis Worked Example

B.4.1 Q-Analysis Algorithm

Recalling figure 7.4 for the incidence matrix Λ , the top- q value is derived from the leading diagonal value of the product matrix:

$\Lambda \cdot \Lambda^T - U$ where

Λ^T = the transposed matrix of Λ

U = the unitary matrix

For the incidence matrix in figure 7.4, $\Lambda \cdot \Lambda^T - U =$

$$\begin{bmatrix} 1 & 1 & 0 & 1 & 0 & 1 & 1 \\ 0 & 0 & 1 & 0 & 1 & 0 & 1 \\ 0 & 0 & 0 & 0 & 1 & 0 & 0 \\ 0 & 0 & 0 & 0 & 1 & 0 & 0 \\ 0 & 1 & 0 & 0 & 0 & 0 & 0 \end{bmatrix} \cdot \begin{bmatrix} 1 & 0 & 0 & 0 & 0 \\ 1 & 0 & 0 & 0 & 1 \\ 0 & 1 & 0 & 0 & 0 \\ 1 & 0 & 0 & 0 & 0 \\ 0 & 1 & 1 & 1 & 0 \\ 1 & 0 & 0 & 0 & 0 \\ 1 & 1 & 0 & 0 & 0 \end{bmatrix} - \begin{bmatrix} 1 & 1 & 1 & 1 & 1 \\ 1 & 1 & 1 & 1 & 1 \\ 1 & 1 & 1 & 1 & 1 \\ 1 & 1 & 1 & 1 & 1 \\ 1 & 1 & 1 & 1 & 1 \end{bmatrix} = \begin{bmatrix} 4 & 0 & -1 & -1 & 0 \\ 0 & 2 & 0 & 0 & -1 \\ -1 & 0 & 0 & 0 & -1 \\ -1 & 0 & 0 & 0 & -1 \\ 0 & -1 & -1 & -1 & 0 \end{bmatrix}$$

Figure B.3 – top- q value calculation

Figure B.3 gives Q-level, *i.e.* the dimension, at which the person will first be present in the structure. To determine the dimension at which the person joins a structure, either of two approaches may be taken. Firstly, the q-geometry may be drawn for the structure (see figure B.4 for people in simplex and node views), or the following algorithm can calculate this:

- (i) take row X and compare with row Y
- (ii) count the number of shared columns (both rows containing "1"). This is the dimension of shared geometry of these two persons. If the number is zero then it may still be possible for them to join a structure at the minimum dimension of connectivity shared with a third party person(s) if they both have that dimension of connection with these persons
- (iii) Repeat for row Y-1 (if not row X)

This appears very complicated. The starting structure from the product matrix calculation tells the researcher which other rows to be looking for to check for a N-dimension connection (*i.e.* if the top-*q* value is not as high as the dimension N, there is no point looking for the bottom-*q* value of that row yet). This enables the simplicial structure of the relationship to be mapped, and each simplex shown in parenthesis against the Q-level concerned.

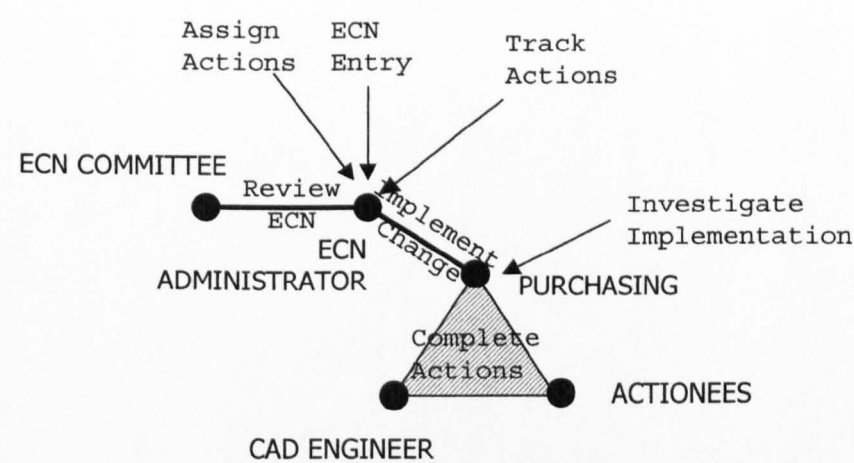


Figure B.4 – person as node representation of the mapping relation

Figure B.5 gives the picture for the person-as-simplex interpretation of the relation.

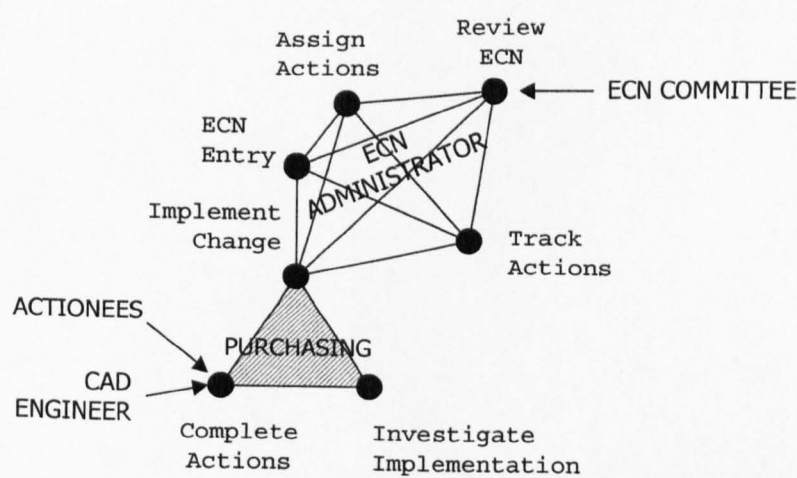


Figure B.5 – person as simplex representation of the mapping relation

B.4.2 Eccentricity Calculation

Recalling equation 4.8,

Eccentricity (Ecc) = (top-q – bottom-q)/(bottom-q + 1)

Figure B.6 expands the results reproduced in figure 7.6:

Participant	ECN Administrator	Purchasing	Actionees	CAD Engineer	Committee
top-q	4	2	0	0	0
bottom-q	0	0	0	0	0
Eccentricity	4	2	0	0	0

Figure B.6 – Eccentricity calculation expansion

APPENDIX C - BACKGROUND FOR INK AND SOLVENT DELIVERY BUSINESS (ISDB)

C.1 The business strategic context for the ISDB process

Whilst Linx is an Original Equipment Manufacturer, and is primarily concerned with the design and supply of industrial printing machines, it also sells inks and top-up solvents for the printers. This is a very lucrative post-sales revenue stream. Only Linx inks and solvents are approved for use in the printers (supported by the rationale that the interaction between machine and ink is a carefully engineered system).

C.1.1 Background of ISDB process

The Products

The products themselves are a mixture of proprietary (*i.e.* formulated in-house) and bought-in speciality inks from third parties. The high volume items are proprietary and made in-house from raw materials. There are twenty-seven inks in the product range, with just two inks accounting for about 75% of the sales by volume. There are fifteen solvents in the product range.

In 2003, over 1 million litres of ink and solvent were manufactured and sold, in a ratio of 5:1 for solvent : ink. There are ten direct employees in the manufacturing plant and dispatch warehouse, supervised by a team leader. In the financial year 2003-04, sales of ink and solvent were worth £8 Million.

During their formulation, inks are validated for each printer in the company's product range, and has a solvent co-specified as a top-up fluid (with the correct formulation to sustain operation of a printer using that ink).

All products are packaged into 0.5 litre bottles with an induction sealed cap closure. Ink is bottled into 45mm diameter neck size bottles, but solvent may be packaged into 38mm or 45mm neck size bottles. The two Stock Keeping Units (SKU's) for each solvent are ten bottles of each neck size in a carton ("5L" pack). There are a further four SKU's for each ink: ten bottles in a carton ("5L" pack); an "Easi" pack of five boxes each of two bottles; a "Combi" pack of four ink bottles with six bottles of solvent in 38mm neck size; a "Combi" pack of four ink bottles with six bottles of solvent in 45mm neck size.

The newer printers are restricted to 38mm neck diameter solvent bottles, and new inks are targeted only at newer printers. The ink is only launched in a 38mm Combi – adding only one SKU per new ink, until it is established with customers. For inks going on general release (all printers), every new ink could conceivably therefore create four new SKU's if it is used in conjunction with an existing solvent, or six new SKU's if a new solvent is also required.

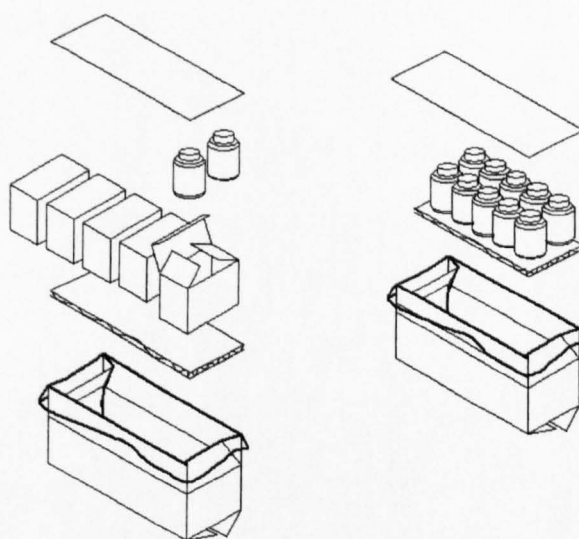


Figure C.1 – "Easi" Pack (left) and "5L" and "Combi" Packs (right)

The packs comprise a carton lined with a plastic bag containing an absorbent shipping pad, ten bottles (packed as shown in figure C.1) and a layer pad on top. This half-litre bottle and five-litre combination pack size were chosen because it is the maximum size package of Class 3 flammable liquids (all inks and solvents are based on organic solvents) that may be sent via airfreight. A complete pallet comprises 112 boxes, or 560 litres.

Solvents generally have a two-year shelf life (six months in-house, eighteen months to the customer), and inks fifteen months (three months in-house, one year to the customer). This policy assures the customer that the products they buy will have a useful minimum shelf life.

The ordering pattern of customers is split between

- Daily (next-day) small quantities of single boxes to end users in the UK (approximately 10% by volume);
- Weekly road, sea and air freight quantities to the company's European and global distributors. This is typically a half to a couple of pallets, with around one hundred cartons per pallet (approximately 40% by volume);
- Scheduled monthly sea freight orders of ten to twenty pallets, usually of bulk solvents to distributors in Asia and the United States (approximately 50% by volume).

C.1.2 Objectives of this process

The stated objectives of the Ink and Solvent Delivery Business (ISDB) are to maximise sales revenue, whilst minimising the cost of ownership to the distributor and making Linx "Easy To Do Business With" ("ETDBW", defined by Hammer (2001), discussed in section 2.3.4). Maximising sales revenue includes a policy of value-based pricing, and policies to deter piracy (the use of other companies' ink and solvent), neither of which are actively pursued through the operation of the ISDB itself. Being "easy to do business with" includes both of:

- Immediate stock availability of all items (shortages and immediate requirements);
- Consolidation of orders for the most economic shipping costs for distributors.

Both of these add uncertainty to the demand for products.

Operational effectiveness is at the heart of the strategy that this process is supporting. The process is currently measured on a weekly basis by a cross-functional senior management team for:

- Percentage of line items (a single order may have a number of lines) shipped On Time In Full (OTIF). The set target is 95%. The performance is typically very high, and runs of seven or more weeks exceeding the target are not uncommon. This measure is a classical outcome measure, rather than a measure of how the delivery process behaved. It is, however, very important because it is customer facing.
- Number of litres of product manufactured (as measured by stock bookings onto the company's Material Requirements Planning MRP system).

These measures record achievement of a service level to customers, and a crude measure of the operational effectiveness and hence future likely customer service level achievement respectively. The latter is based on the rationale that if products are not made this week, they will not be available to send to customers next week. This is actually at odds with the process trigger of making only on demand, either to replenish finished goods kanbans or for a particular large order. It is also an attempt to gauge the operational effectiveness of the plant.

Based on the drivers of OTIF and the economics of production, and following a Balanced Scorecard approach, the following operational measures have been adopted by the ink manufacturing team (*i.e.* for the process in C.3):

- First Time Pass Rate (FTPR) at vessel Quality Control testing – the proportion of batches which pass first time and without adjustment;
- Actual plan adherence against hourly targets (for Manufacturing Activity in figure C.3);
- A log of lost “opportunities” and reasons for downtime in the individual sub-activities of figure C.3;
- Expired finished goods and raw material stock, scrap packaging materials (caps, bottles, cartons);
- Process yield on a per-batch basis;
- Coverage of each skill area on the skills matrix (see figure C.4).

C.1.3 Discussions with stakeholders

The following discussions were carried out:

- Mr A – ink manufacturing team leader;
- Ms B – sales order processing manager;
- Mr C – shipping clerk (part of sales order processing group);
- Mr D – finance director.

There was broad agreement amongst all persons that the objective was to achieve a high level of OTIF delivery to customers, and that this top-level measurement was fair and accurate. There was a similar consensus that the quality of products shipped to customers were second to none, and that this was not a concern.

The measure of litres of ink/solvent was felt by Mr A to be unfair because it did not reflect the impact of product mix on the week's output. Products that are difficult or slower to make are equally important to customers but that credit is not given for them by this measure. The greatest operational problem Mr A experiences is not having operators with the right skills to carry out activities without direct supervision. This includes organising themselves to do simple things like good housekeeping in the plant. Mr A also felt that questions posed over current and future capacity issue can be best resolved by investment in a pilot line for the lower volume and speciality products, removing them from the automated line.

Ms B was concerned that there was not the visibility of future stock levels, against which consolidated orders could be managed and delivery dates confirmed to customers. Ms B felt that despite poor personal visibility, that Mr A made good production plans and could normally be expected to have stock available for her customers. If she had any concern about the process it is that the skill appears to be restricted to Mr A, and that service might deteriorate when he was absent. The same could be said of sales order processing group's experience of variability in quality of service in the dispatch warehouse with changes of assigned operator.

Mr C felt that there was not enough flexibility in the way that orders are consolidated to allow for rescheduling their dispatch. He has no concerns for the capacity or capability of the unit to cope with increased volumes.

Mr D was pleased with the performance of the team and its contribution to the financial performance of the company. However, he was concerned that the ISDB has just enough manufacturing capacity to keep going at present demand rates, and was not comfortable with the longer-term outlook for the unit. He was also aware that the business climate might be changing and that the company may not always be guaranteed a high margin revenue stream from its inks and solvents, due to increased piracy or legislation.

To summarise, the following key operational effectiveness issues are of interest to some or all stakeholders:

- There is a need for a more reasonable performance measure than litres of product to reflect the operational effectiveness of production planning and plan execution in the manufacturing unit;
- The degree of dispersion of skills amongst operators and their ability to self-organise needs to be reviewed;
- There needs to be the ability for the dispatch activity to be more flexible with shipper schedule changes;
- The current and future achievable manufacturing capacity needs to be understood, particularly the potential merit of adding capacity by the introduction of a pilot line, and the challenge to the operating dictate that all products should be available in stock (see figure C.2).

C.2 Detailed operation of the ISDB process

C.2.1 Process Mapping

Figure C.2 shows A process map for the process from customer order arrival to dispatch:

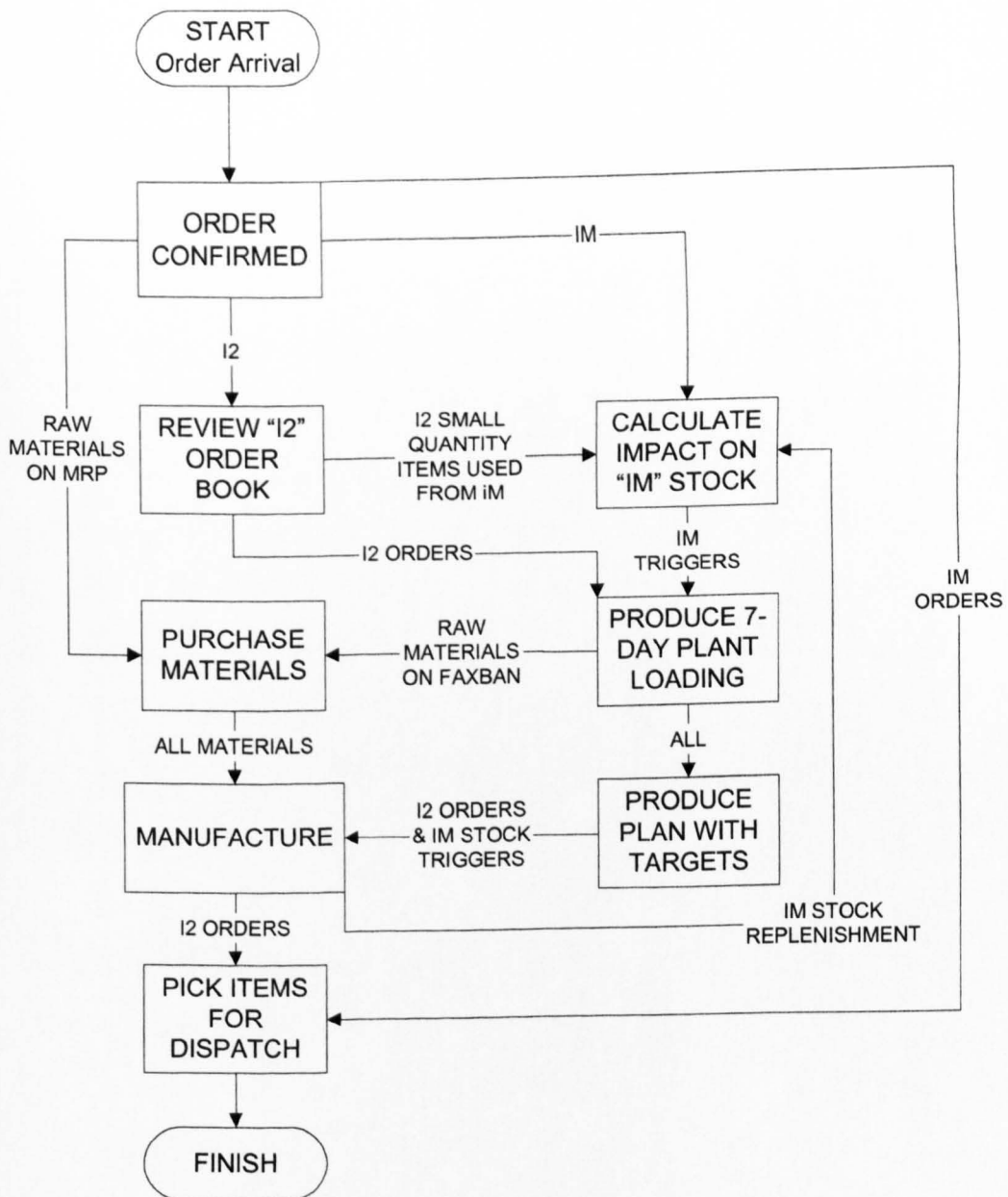


Figure C.2 – Overview of the process, including the split between "IM" and "I2" orders

This map shows that there are two distinct categories of orders, "IM" and "I2" orders. "IM" orders make up the vast majority number of separate transactions, around 99% (based on an analysis in 2002). An "IM" order can be inclusive of a several pallets of mixed products, or as little as one box. "I2" are large sea freight orders (on a four week lead time), and typically making up ten or twenty pallets of products in a single transaction (for a twenty of forty foot container). These are typically 1% of orders (just forty in the 2002 study) in terms of transactions, but account for around 50% of products by volume.

The process map shows that products for "IM" orders are taken from a replenished stock, managed through the "IM" data warehouse on the MRP system. The stock level has a re-order point and quantity, based on batch size, typical demand, and internal lead-time for manufacture before the stock is available again. "I2" orders are large, scheduled and made to order, with any small quantities or odd products being made up from the "IM" stock. The "I2" stock is in a separate warehouse on the MRP system.

Before this warehouse split was instigated (following the aforementioned study in 2002), the single warehouse was inadequate for the needs of both types of order. The result was a destructive cycle of stock allocation (to a long lead time order), poor visibility of actual free stock for immediate use and demand amplification of short-term plant loading to meet all outstanding orders. This prompted poor overall delivery performance and constant and widespread concerns about adequate capacity. These concerns fuelled further advanced allocation of stock as soon as it became available, regardless of when it was needed.

The split of orders between the "IM" and "I2" electronic warehouses is responding to two different demand patterns by making to stock and making to order respectively. Making to a fixed stock level is a lean process, where the inventory is buffering the requirement for a stream of products in a high variety mix at short notice, replenished as frequently as possible by a highly efficient production system operating under its constraints of batch size *etc.* The emphasis of the system is on its ability to replenish triggered kanbans. The lean objective is to reduce batch sizes and set-ups to reduce this stock and converge onto a solution of being able to make every product every day, to meet customer demand in real time.

Making to order is essentially an agile response to a different problem, the system having enough free capacity set aside to make the requirements to order. This is the extent of the espoused agility and there are no other elements that one would identify with agility such as pursuing "economies of scope" (see section 2.3.3). A four-week lead-time is requested on this type of order, but this is usually independent of production or material constraints and is simply a result of the backlog of orders. The belief is that offering shorter lead times would not make Linx more

"easy to do business with" because customers are required to arrange these shipments long in advance with freight forwarders. Delivering on the agreed due date is therefore far more important than how much notice has to be given, and this will remain the case until it becomes possible to shorten international shipping lead times.

The lean-agile split for demand management from customers is applied across the entire product range, with the same stocking policy for both bulk high volume (rapid turnover) products and specialist, low volume products. The only crossover between the electronic warehouses is that small quantities of certain items can be consumed from the "IM" warehouse stock to complete an "I2" order. All products are effectively treated the same by the ISDB process, even though the detailed manufacturing steps are quite different. This assumption will be raised as an issue for the EAR hierarchy to explore.

All upstream purchasing is a mixture of:

- lean replenishment re-ordering through "faxban" (faxed messages pulling a fixed delivery quantity of high volume materials such as bulk solvents, packaging materials *etc.*);
- Conventional Materials Requirements Planning (MRP) based around maintaining stock levels calculated using lead-time and historically generated forecasts of demand. The MRP run associated with order arrivals also reduces stock levels and feeds a standard feedback loop of materials purchasing via the MRP system.

As soon as they are confirmed by sales order processing group, all "IM" orders are output on a 7-day rolling demand report for the manufacturing team. This gives the team advance notice of the "IM" stock kanbans that will trigger in the next seven days. In conjunction with the requirements of the "I2" warehouse in the next seven days, a plant-loading graph is produced. The seven-day plant loading forms a basis for daily production planning, and advance ordering via "faxbans".

Batches of products are then made to a daily plan, and booked into finished goods stock once complete. The manufacturing process for the 5L pack (the vast majority of product) is

summarised below. This is irrespective of whether the finished stock is booked into the “IM” or “I2” electronic warehouses.

“IM” orders are then picked on a daily picking list basis sent down to the warehouse from the sales order-processing group. This includes short lead time consolidated orders (regular weekly orders) and orders received for immediate dispatch via overnight courier. “I2” orders are consolidated over time as stock is made.

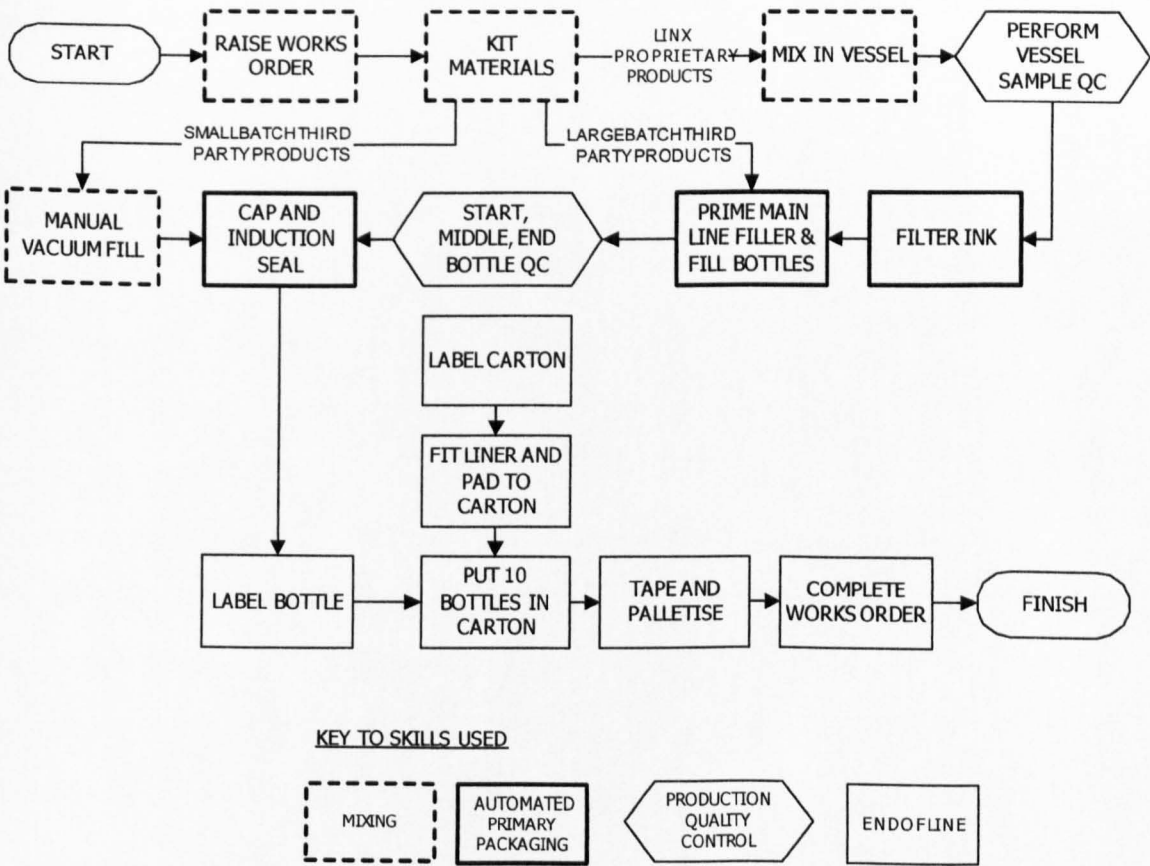


Figure C.3 – 5L pack manufacturing.

The process in Figure C.3 is the MANUFACTURE sub-process in Figure C.2. This more detailed figure shows that there are four recognised skill sets of adjacent operations (both geographically and in process sequence) to make ink and solvent products in the 5L pack format. Much of the physical processing is carried out by automated equipment, and the skill area involves being able to set-up, changeover and operate the equipment. The exception here is the manual operation

of MANUAL VACUUM FILL, which is reserved for small batch third party products bought in and packaged by Linx for reselling as part of their product range.

All operations are specified by a written procedure called a work instruction. These are written, peer-reviewed and maintained under issue control by operators.

"Combi" and "Easi" packs are made to order in the dispatch warehouse on a separate, flexible piece of labelling equipment by consuming the 5L stock into the required packs and adjusting MRP stock records accordingly. This is carried out in the activities of PICK ITEMS FOR DISPATCH in Figure C.2.

C.2.2 Entity-Activity-Resource definitions and set memberships

The Entity, Activity and Resource definition are now required. This is iterative with the aggregation of the process for simplicity and to confirm that the key issues and system components are being included in the study. Starting with the Entity, an inspection of the process in Figure C.2 would imply that a customer order is the most important entity from the process. However, Figure C.3 implies that the unit of output is the batch of manufactured stock in either the "IM" or "I2" warehouses. Usually the principal that the entity that is closest to the customer is the most important one (and in this case is consistent with a key performance measure (OTIF) for the process), then customer orders will be taken to be the Entity set.

The analysis of customer orders involved analysis of three months' order entry data. This entailed analysing around one thousand transacted orders with from one to several tens of lines (products and quantities) per order. Each line of an order was for a different amount of one of one hundred and forty different Stock Keeping Units. This was simplified, based on the following assumptions of how the ISDB process "sees" customer orders:

- The manufacturing operation in the plant (see figure C.3) really sees seven different types of process, regardless of neck size, product *etc.* This is because the batches are treated separately; with a cleaning regime between them to prevent any cross

contamination. Neck size changes for solvents (necessitating a change in bottle and closure) are carried out during the change from batch to batch and are transparent in this simplification exercise. There are thus seven "meta-products" made in the plant;

- The proliferation of SKU's based on "combi" and "easi" packs is made to order as a dispatch activity in the warehouse (this was done intentionally by the manufacturing team to remove the disruption of these) and can be effectively ignored in manufacturing operations;
- At dispatch, each product is treated as the same, regardless of which of the seven meta-products it is. It could have been possible to simplify the dispatch model to just number of boxes picked, but this would lose important data about the coupling of the manufacturing and dispatch operations, *i.e.* the "IM" kanban stock sizes. The quantities of these seven simplified meta-products picked at dispatch have been clustered into four Dispatch quantities (D) of boxes of each of the meta-products
 1. $D \leq 10$
 2. $10 < D \leq 40$ (40 was chosen from the experience of the warehouse staff as a good break point in the likely spread)
 3. $40 < D \leq 112$ (112 chosen because it is 1 pallet of boxes)
 4. $112 < D$ (*i.e.* a multi-pallet order from "I2")
- Orders may be categorised as "IM" for immediate picking or "I2" based on a single weekly requirement.

Based on these assumptions, a set of thirty types of order Entities of "IM" and "I2" was adopted.

The Activity set is more apparent insofar as it is a combination of the process steps detailed in Figures C.2 and C.3. The degree of abstraction of the process steps must reflect both the needs of the Entities and Resources. The process of precise definition of the Activity set is iterative with defining the Entities and Resources and with aggregation. The set of Activities has been related to the seven formally assessed skills and two other key skills – sales order processing and production planning, a total of nine distinct skills.

The Resource set was taken to be the ten people working in the manufacturing and warehousing area, plus a representative from the sales order-processing group. This is a total of eleven people.

C.2.3 Process Aggregation

An obvious requirement is that the aggregated process must still be recognisable to the stakeholders. Also, the remaining activities may be represented in a discrete model that bears some relation to the available validating data available from the real system. There must also be a clear mapping relation between the Activities and skills contained therein. This can be many-to-one or one-to-many, but must not overlap such that any two skills appear in other activities (*i.e.* many-to-many). There must also be a distinct set of queue-servers to allow both the entropy observations and discrete event modelling.

The aggregated process is a set of seven activities (with associated queues and skills) in figure C.4. This forms the basis of both entropy observations.

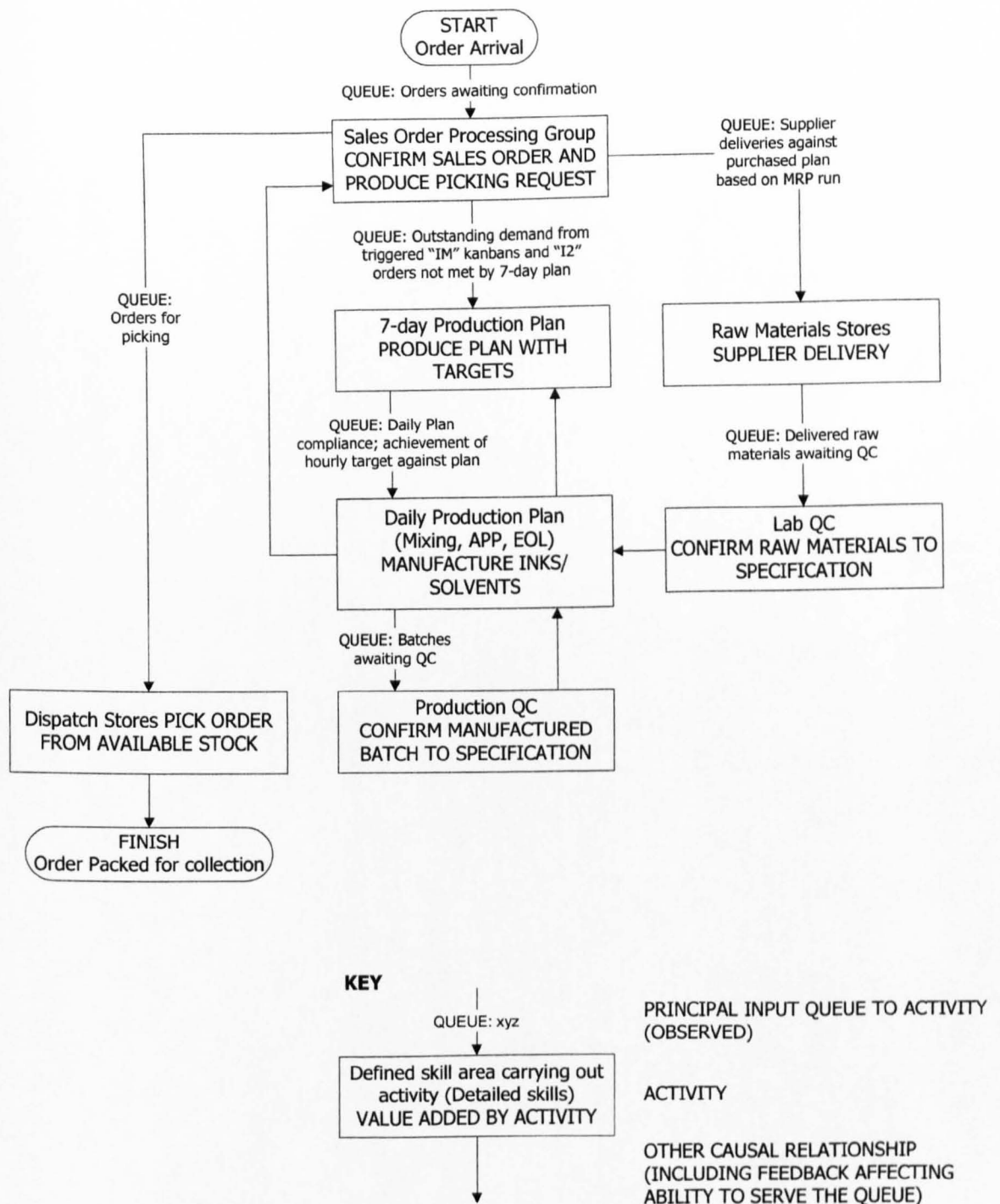


Figure C.4 – process map used in study

This figure shows the final set of activities and queues observed in the study, which is also the skill set used as the basis for the Activity – Resource mapping relationship. In the MANUFACTURE INK/SOLVENT activity, three detailed skills are defined, and it is these that are used for subsequent Q-analysis. This aggregation was made because it would not be possible to meaningfully observe each of these skills in operation within an expanded set of activities (they

are much shorter cycle time activities and would not fit with the rest of the system). If obstacles to flow or other concerns are identified at this abstracted level of study, they provide a basis for a more detailed investigation of the manufacturing activity as a whole sub-process in itself.

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